U.S. Department of the Interior
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Marvin A. Lanphere[1], Mel A. Kuntz[2], and Duane E. Champion[1]

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[1]Branch of Isotope Geology
345 Middlefield Road
Menlo Park, CA 94025

[2]Branch of Central Regional Geology
Denver Federal Center
Denver, CO 80225

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ABSTRACT

The petrography, age, and paleomagnetism were determined on basalt from 21 lava flows comprising about 1,700 feet of core from two coreholes (TAN CH#1 and TAN CH#2) in the Test Area North (TAN) area of the Idaho National Engineering Laboratory (INEL). Paleomagnetic studies were made on two additional cores from shallow coreholes in the TAN area. K-Ar ages and paleomagnetism also were determined on nearby surface outcrops of Circular Butte Paleomagnetic measurements were made on 416 samples from four coreholes and on a single site in surface lava flows of Circular Butte. K-Ar ages were measured on 9 basalt samples from TAN CH#1 and TAN CH#2 and one sample from Circular Butte. K-Ar ages ranged from 1.044 Ma to 2.56 Ma. All of the samples have reversed magnetic polarity and were erupted during the Matuyama Reversed Polarity Epoch.

INTRODUCTION

The U.S. Geological Survey currently is studying the petrology, paleomagnetism, and age of basalt lava flows in several coreholes at the Idaho National Engineering Laboratory (INEL) The INEL is located between Arco and Idaho Falls in southeastern Idaho (Fig. 1). The current program is a continuation of studies begun in 1974 to evaluate potential volcanic hazards at INEL. These studies have included geologic mapping and various studies of surface lava flows such as petrologic and paleomagnetic investigations and radiometric age measurements. Previous investigations also were carried out on selected drill cores from several different coreholes in the southern part of the INEL.

The present project was begun in 1989 with the objective of studying, in some detail, core samples from several wells in the INEL. The specific coreholes named in the project proposal were Well 80, TAN CH#1, NRF 89-04, NRF 89-05, ICPP 123, 2-2A, and WO-2. The purpose of the proposed investigations was to develop a three-dimensional stratigraphic framework for geologic and hydrologic studies including potential volcanic hazards to facilities at the INEL and movement of radionuclides in the Snake River Plain aquifer. Funding for this research project has been provided by the U.S. Department of Energy.

Our first report dealt with investigations on Well 80, NRF 89-04, NRF 89-05, and ICPP 123 (Lanphere and others, 1993), and included paleomagnetic measurements, potassium-argon (K-Ar) age measurements, and petrographic characteristics of basalt lava flows. This report covers similar investigations in Test Area North including coreholes TAN CH#1, TAN CH#2, GIN-5, and GIN-6.

GEOLOGIC SETTING

The INEL covers an area of about 2,300 km^2 in the eastern Snake River Plain (Fig. 1), which is a northeast-trending structural trough containing Neogene volcanic rocks and interbedded sediments. Rhyolitic flows are generally exposed only along the margins of the Plain, but several domes, surrounded by basalt flows, are located in the plain. Most of the eastern Snake River Plain is covered by late Pleistocene and Holocene basalt lava fields.

The surface geology of the INEL has been studied and a number of wells have been drilled to provide subsurface information. Kuntz and others (1984, 1994) published geologic maps of the INEL and adjoining areas and described the petrography, age, and paleomagnetism of basalt flows penetrated in ten cored holes at the Radioactive Waste Management Complex (RWMC) in the southwestern part of the INEL (Fig. 1). A subsequent cored hole (site E), drilled about 10 miles (16 km) northeast of the RWMC, was studied by Champion and others (1988).

Lava flows at the INEL are very similar petrographically. All are olivine basalt containing olivine, plagioclase, clinopyroxene, titanomagnetite, ilmenite, glass, and accessory apatite and zircon(?). There are significantly different textural varieties in the basalt flows even though the mineralogy remains similar. In the subsurface, some of the lava flows are separated by lenticular sedimentary interbeds.

K-Ar ages of surface flows in the INEL range from 55 ± 50 ka (10^3 yr) to 1216 ± 50 ka (Kuntz and others, 1980, 1990, 1994). The oldest ages reported for lava flows in the subsurface in the southern part of the INEL are 641 ± 54 ka for the deepest flow in the site E well (Champion and others, 1988), 643 ± 64 ka in Well 80 (Lanphere and others, 1993), and 653 ± 49 ka in ICPP 123 (Lanphere and others, 1993). All of the lava flows in coreholes in the southern part of the INEL (Lanphere and others, 1993) have normal polarity and must be younger than about 780 ka, which is the age of the boundary between the Brunhes Normal Polarity Chron and the Matuyama Reversed Polarity Chron (Shackleton and others, 1990). The age of 819 ± 39 Ma measured on the deepest flow in NRF 89-04 (Lanphere and others, 1993) agrees with the age of the polarity boundary within analytical uncertainty and is compatible with the magnetic polarity data

Surface lava flows and vents in the southern part of the INEL have normal polarity and were erupted during the Brunhes Normal Polarity Chron. Surface lava flows and vents in the northern part of the INEL are reversely magnetized and were erupted during the Matuyama Reversed Polarity Chron. In well 77-1 at the RWMC there are two lava flows with reversed polarity (Champion and others, 1981); a K-Ar age of 565 ± 14 ka was measured on these flows (Champion and others, 1988). A reversely magnetized flow having a magnetic inclination similar to flows 10 and 11 in well 77-1 occurs in the corehole at site E. These reversely magnetized flows were erupted during a polarity event named the Big Lost Reversed Polarity Subchronozone and Subchron by Champion and others (1988). Reversely magnetized flows are not present in Well 80, ICPP 123, and NRF coreholes studied by Lanphere and others (1993).

ANALYTICAL TECHNIQUES

Selected cores were carefully logged and sampled for petrographic studies. The logging involved description of core material, location of tops and bottoms of lava flows, and preparation of lithologic logs. The lava flows were sampled for thin section analysis at various intervals. Samples were taken from flows to represent the top, middle, and bottom, and also to give representative textural varieties of the flow. Thin sections were studied using standard microscopic methods. Depths were measured by tape measure from known depths recorded on wooden plugs in core boxes. The color of flows was determined by comparison to standard color chips in the Munsell Soil Color Charts. Textures and minerals were identified using a hand lens and petrographic microscope. Phenocryst sizes were determined from thin sections using a micrometer ocular.

For paleomagnetic studies, seven samples of core, generally 6 cm in diameter, were taken from each flow. For each sample a 2.5 cm-diameter core was drilled at right angles to the axis of the original core to provide material for magnetic analysis. These mini-core specimens were trimmed to 2.2-cm lengths, and inclination and intensity of magnetization were measured with a spinner magnetometer.

Thin sections of 40 samples of basalt from TAN CH#1 and TAN CH#2 drill cores were examined petrographically to determine those most suitable for K-Ar dating. Nine samples were chosen for analysis; these samples met the usual criteria of acceptability for whole-rock K-Ar dating (Dalrymple and Lanphere, 1969; Mankinen and Dalrymple, 1972). The samples were selected to minimize the amount of glass in the groundmass; the amount of glass in the samples used for age determination is considered too small to affect the measurements. The samples were crushed and ground to a size of 1/2 to 1 mm. An aliquant (10 g) of the sized master sample was pulverized to less than 74 μm, and this powdered material was used for the K_2O measurements. The K_2O measurements were made in duplicate on each of two splits of powder by flame photometry after lithium metaborate fusion and dissolution (Ingamells, 1970). Argon analyses were made by isotope dilution using equipment and techniques described previously (Dalrymple and Lanphere, 1969). Aliquants of the 1/2-1 mm master sample were baked overnight in vacuum in an argon extraction system at 280°C. Ar mass analyses were done on a computerized multiple-collector mass spectrometer with 22.86-cm radius and nominal 90°-sector magnet (Stacey and others, 1981). The analytical error for an individual age measurement was calculated using the method of Cox and Dalrymple (1967). Weighted mean ages for lava flows were calculated using the method of Taylor (1982).

One sample in this study was analyzed using the $^{40}Ar/^{39}Ar$ technique (Dalrymple and Lanphere, 1971; Lanphere and Dalrymple, 1971). This technique employs a different approach to using the radioactive decay of ^{40}K to ^{40}Ar as a chronometer. In the $^{40}Ar/^{39}Ar$ method the sample is irradiated with fast neutrons, along with a monitor mineral of known age, to induce the reaction $^{39}K(n,p)^{39}Ar$. The age of the sample is calculated from the measured $^{40}Ar/^{39}Ar$ ratio after determining the fraction of ^{39}K converted to ^{39}Ar by analyzing the monitor mineral. Corrections for interfering Ar isotopes produced from K and Ca and for atmospheric Ar must be made. An important difference between the conventional K-Ar method and the $^{40}Ar/^{39}Ar$ method is that quantitative measurements of the contents of radiogenic ^{40}Ar and ^{40}K in a sample are required by the conventional reversed polarity and yielded flow-averaged inclination values ranging from -47.4° to -73.5°. Error envelopes about these means are small (~2°), except for the bottom flow in TAN CH#2, which had too few specimens. The flow mean inclination values suggest patterns of eruptive simplicity within the stratigraphic sequence. Despite the petrographic differences between numbered flows, the mean inclination values for sequential flows commonly are nearly identical. This suggests that very little time elapsed (<100 years) during eruption of the flow sequences. Thus, the number of eruption episodes may be only a small fraction of the number of flows.

The virtually constant motion of the geomagnetic field vector with time offers an opportunity to use paleomagnetic measurements to identify very short breaks in sequences of lava flows. Angular motions averaging 4° to 5° per century can be documented in Holocene and latest Pleistocence lava flows (Champion and Shoemaker, 1977). Individual Holocene lava flows on the surface of the Snake River Plain having volumes of ~4 km^3 show only a single direction of magnetization. This indicates that the lava fields were erupted before the magnetic field vector could move to a new analytical resolvable position (typically about 4°), and, therefore, took no more than about 100 years to form. This surface-justified model of the duration of lava field formation has been carried into the subsurface and utilized in the study of INEL drill cores. The results for individual core holes are discussed below.

TAN CH#1

TAN CH#1 was cored to a depth of 600 ft and contains thirteen lava flows. Only two eolian and alluvial sediment interlayers occur in the corehole. A log of the core stratigraphy and paleomagnetic inclinations is given in Figure 2.

Paleomagnetic measurements

Remanent magnetic inclination values were measured on 126 samples from 13 lava flows in corehole TAN CH#1. All lava flows sampled have reversed polarity; and presumably were erupted during the Matuyama Reversed Polarity Epoch. Although 13 distinct flows were identified in logging and petrographic studies, only 5 independent inclination groups were recognized in the paleomagnetic data. The mean lava flow inclination values, in descending order of depth, are:

Flow #	Depth	Inclination
1	44 - 70'	-65.5° ± 2.0°
2	70 - 104'	-67.0° ± 1.9°
3	104 - 138'	-71.3° ± 3.5°
4	138 - 186'	-70.8° ± 1.4°
5	186 - 225'	-72.7° ± 3.4°
6	226 - 289'	-71.2° ± 1.1°
7	289 - 339'	-72.8° ± 0.7°
8	339 - 353'	-70.1° ± 1.9°
9	353 - 401'	-71.4° ± 2.1°
10B	412 - 443'	-50.2° ± 3.9°
11	*(flow in TAN CH#2 not petrographically recognized at this site)*	
12	448 - 506'	-66.3° ± 1.3°
13	506 - 544'	-67.5° ± 1.7°
14	544 - 600' (total depth)	-67.0° ± 1.2°

It is not clear that flows 3 through 9, and flows 12 through 14, represent independent eruptive events, as they are not separated by any sedimentary interbeds in TAN CH#1. These flows share similar paleomagnetic inclination values which means that each flow sequence could each have formed in a short period of time (<100 years). Though they are petrographically distinct, it is possible they represent flows from multiple vents during a single eruptive episode. If they are similar in age, then the average inclination value for the time represented by flows 3 through 9 (104 - 401') is -71.5° ± 0.6° and for flows 12 through 14 (448 - 600') is -66.8° ± 0.7°.

K-Ar age measurements

Duplicate K-Ar ages were measured on three samples from TAN CH#1--one sample each from flows 4, 10B, and 13. Three ages were measured on a sample from flow 2. Ages and analytical data are given in Table 1. The ages range from 1.044 ± 0.035 Ma to 1.936 ± 0.083 Ma and are in the correct stratigraphic order with ages increasing with depth The upper three flows lie on a linear lava accumulation curve indicating a nearly constant rate of accumulation. However, there was a significant hiatus in eruption sometime between the eruption of flows 10 and 13.

TAN CH#2

TAN CH#2 was cored to a depth of 1113.5 ft and contains nineteen lava flows Seven eolian and alluvial interbeds occur in the corehole. A log of the core stratigraphy and paleomagnetic inclinations is given in Figure 2.

Paleomagnetic measurements

Remanent magnetic inclination values were measured on 194 samples from 19 lava flows in corehole TAN CH#2. All lava flows have reversed polarity and presumably were erupted during the Matuyama Reversed Polarity Epoch. Although 20 distinct flows were identified in logging and petrographic studies, only 7 independent inclination groups were recognized in the paleomagnetic data. The paleomagnetic data suggest 7 eruption episodes in TAN CH#2, each <100 years in duration. The lava flow mean inclination values, in descending order of depth, are:

Flow #	Depth	Inclination
1	47 - 75'	-65.0° ± 0.7°
2	75 - 134'	-67.9° ± 2.0°
3	134 - 159'	-70.3° ± 2.3°
4	159 - 224'	-71.6° ± 1.0°
5	224 - 239'	-70.6° ± 1.9°
6	247 - 305'	-71.4° ± 2.2°
7	305 - 330'	-71 6° ± 3.6°
8	330 - 346'	-71.5° ± 0.8°
9	346 - 448'	-70.6° ± 1.4°
10A	452 - 469'	-62 9° ± 3.1°
11	473 - 548'	-64.3° ± 1.3°
12	*(flow in TAN CH#1 not petrographically recognized at this site)*	
13	549 - 584'	-64.0° ± 1.9°
14	586 - 646'	-69.0° ± 1.8°

15	646 - 699'	-66.9° ± 1.0°
16	699 - 733'	-66.2° ± 1.8°
17	742 - 877'	-50.1° ± 0.9°
18	877 - 977'	-50.3° ± 1.0°
19	981 - 1033'	-47.4° ± 0.8°
20	1033 - 1093'	-49.3° ± 0.6°
21	1102 - 1114' (total depth)	-52.2° ± 11.8°

The paleomagnetic data suggest that the sequences of flows 3 through 9, flows 11 and 13, flows 14 through 16, and flows 17 through 21, were produced during four independent eruptive events because the flows in each sequence have similar inclination values. Some of these sequences have thin, intercalated sedimentary interbeds, but these interbeds cannot represent significant time breaks. Though the numbered lava flows within a sequence having similar inclination values are petrographically distinct, it is possible they represent flows from multiple vents produced during a single brief eruptive episode. If the episodes are short-lived, then the thin sedimentary interbeds at 239 - 247' and 977 - 981' would have to result from very brief eolian depositional events during the cycles in which the lava flows were erupted. This contrasts with the commonly held notion that sedimentary interbeds in these cores require at least thousands of years to form, which effectively breaks the flow sequence into differently timed episodes. Additionally, because these interbeds occur 100's of feet up within a single-inclination group of flows, a question about the efficiency of eolian deposition during the eruptive cycle is posed. With the data in hand, we cannot choose between the possibility that these flow sequences represent eruptive events of brief duration or, alternatively, that the sedimentary interbeds represent a significant hiatus in lava accumulation.

If the inclination flow groups are similar or identical in age, then the average inclination value for the time represented by flows 3 through 9 (124 - 448') is -71.0° ± 0.7°, for flows 11 and 13 (473 - 584') it is -64.2° ± 1.0°, for flows 14 through 16 (586 - 733') it is -67.4° ± 0.9°, and for flows 17 through 21 (742 - 1114') it is -49.7° ± 0.5°.

K-Ar age measurements

Duplicate K-Ar ages were measured on four samples from TAN CH#2--one sample each from flows 10A, 14, 17, and 19. Three ages were measured on a sample from flow 11. Ages and analytical data are given in Table 2. The ages range from 1.412 ± 0.047 Ma to 2.556 ± 0.035 Ma. The ages for flows 10A and 11 differ by more than 600,000 years indicating that the interbed between these flows represents a significant amount of time

GAS-INJECTION TEST WELLS - GIN-5 and GIN-6

Cores from two additional coreholes from the TAN area (Fig. 3) were sampled for paleomagnetic studies. These shallow coreholes were drilled in 1966 to evaluate the feasibility of disposing of gaseous radioactive wastes in the subsurface. No detailed petrographic analysis or geochronologic study was made of these cores, and only the most cursory hand-specimen examination was made. The mean lava-flow inclination values from these samples allow us to extend a 3-mile-long NW-SE line of section (figure 4) through the TAN area that includes coreholes TAN CH#1 and TAN CH#2. The lava flow mean inclination values, in descending order of depth, are:

GIN-5

Flow #	Depth	Inclination
1	23 - 70	-65.8° ± 1.5°
2	80 - 146'	-64.1° ± 1.8°
3+	157 - 430'	-72.2° ± 0.9°

GIN -6

Flow #	Depth	Inclination
1	*(this flow is not petrographically recognized in GIN-6)*	
2	59 - 114'	-64.1° ± 2.9°
3+	119 - 200'	-73.5° ± 1.0°

Flow #1 does not extend northwest from GIN-5 to GIN-6, and seems to decrease in thickness to the northwest from its known source vent at Circular Butte. Flow #2 thins at the location of TAN CH#1. The flows at the bottom of GIN-5, from 157' to 430', all have inclination values in the low -70's; we generally correlate these flows with the sequence of flows 3 through 9 in TAN CH#1 and TAN CH#2 which share the same mean inclination values. Without detailed petrographic study, no direct flow to flow correlation can be made between the lower part of GIN-5 and the TAN coreholes.

CIRCULAR BUTTE

Circular Butte is a volcanic edifice located about three and a half miles southeast of Test Area North. The top of Circular Butte is approximately 250 feet higher than the surrounding plain. The lava flows erupted from Circular Butte flow are porphyritic and contain large tabular crystals of plagioclase as long as 2 cm; this flow is petrographically identical to flow #1 in TAN CH#1, TAN CH#2, and GIN-5.

Paleomagnetic measurements

Paleomagnetic measurements were made on samples from a single surface site at Circular Butte. Site 4B799 is located in a roadcut on Highway 88 close to the location of a K-Ar sample. Vector component analysis on remagnetization planes due to lightning strikes for 8 of 12 cores produce a mean remnant direction with I = -67.6°, D = 189.8°, and alpha 95 = 2.8°. These data along with paleomagnetic data from other INEL surface flows were published by Kuntz and others (1994).

K-Ar age measurements

A sample for age measurement, 84ILe-2, was collected in the Circular Butte lava field from a roadcut on Idaho Highway 88, approximately three-quarters of a mile north of the summit of Circular Butte. Three separate Ar measurements were made on this sample. The reproducibility of the measurements was not particularly good; the measurements yielded a mean K-Ar age of 1.094 ± 0.086 Ma for the Circular Butte lava(Table 3). No ages were measured on flow #1 in either TAN corehole, but the age of 1.044 ± 0.035 Ma for flow #2 in TAN CH#1 is in good agreement with the age for Circular Butte.

An aliquant weighing 155 mg of the same size fraction of 84ILe-2 used for the conventional Ar measurements was irradiated in the U.S. Geological Survey TRIGA reactor for 2 hours. The sample was heated incrementally to progressively higher temperatures in a resistance-heated furnace attached to the GLM continuous laser extraction system (Dalrymple, 1989). Ages were calculated for the Ar released in each temperature increment (Table 4), and these ages are plotted in an age spectrum diagram (Fig. 5). Criteria for interpreting $^{40}Ar/^{39}Ar$ incremental-heating data have been suggested by Lanphere and Dalrymple (1978). The results for 84ILe-2 basalt are consistent with all four criteria. The well-defined plateau in the age spectrum diagram contains 96 percent of the Ar released. The gas increments included in the plateau produce well-defined isochrons (Fig 6) that have $^{40}Ar/^{36}Ar$ intercepts in good agreement with the atmospheric value of 295.5. Also, the plateau age of 1.090 ± 0.013 Ma is in good agreement with the isochron age of 1.074 ± 0.029 Ma.

The $^{40}Ar/^{39}Ar$ plateau age of 1.090 ± 0.013 Ma agrees well with the conventional K-Ar age of 1.094 ± 0 086 Ma for the Circular Butte lava. The plateau age is more precise than the conventional age; thus, the best age for Circular Butte is about 1.09 ± 0.09 Ma.

DISCUSSION

The lava flows of Circular Butte can be correlated confidently with flow 1 in both TAN coreholes on the basis of distinctive texture. The paleomagnetic inclinations of the Circular Butte lava flow and flow 1 in both TAN coreholes and GIN-5 agree within analytical uncertainties Ages were not measured on flow 1 in either corehole. The K-Ar age of 1.044 ± 0.035 Ma for flow 2 in TAN CH#1 agrees within analytical uncertainty with the $^{40}Ar/^{39}Ar$ plateau age of 1.090 ± 0.013 Ma for the lava of Circular Butte though the ages are not in the correct stratigraphic order.

The magnetic polarity of flows 1 and 2 provides a basis for deciding whether the 1.044 Ma K-Ar age for flow 2 is too young or the 1.090 Ma $^{40}Ar/^{39}Ar$ age for flow 1 is too old. All flows in this study have reversed polarity, presumably acquired during the Matuyama Reversed Polarity Chron. The Jaramillo Normal Polarity Subchron is entirely within the Matuyama and is thought to span a time interval between 0.99 Ma and 1.07 Ma (Shackleton and others, 1990). The 1.09 Ma age for flow 1 is consistent with the magnetic reversal time scale, but flow 2 has the wrong polarity for an age of 1.044 Ma, and the correct age must be older than 1.07 Ma. Flow 2 also must be older than the age of 1.09 Ma measured on flow 1.

Flows 1 through 9 in both TAN coreholes correlate well on the bases of petrography and paleomagnetic inclination. The only other K-Ar age in this interval is the 1.248 ± 0.069 Ma age on flow 4 from TAN CH#1 which falls in the correct stratigraphic order.

Correlations of flow 10 between TAN CH#1 and TAN CH#2 by petrographic characteristics are not clear. A distinctive coarse-grained lava between sedimentary interbeds is cut by TAN CH#1 and TAN CH#2. It is probable that this is the same flow. Some petrographic evidence, however, suggests that two flows may be present. The rock in TAN CH#2 has textural characteristics that are different from flow 10 rocks in TAN CH#1. In TAN CH#2, this rock is distinctly olivine phyric, containing subhedral to euhedral phenocrysts of olivine as large as 2 mm. Olivine crystals in Flow 10 rocks in TAN CH#1 contain anhedral-subhedral olivine crystals that are all <1 mm. Detailed chemical data may be necessary to resolve the one flow-two flow problem.

Both the inclination data and K-Ar ages suggest that flows 10A and 10B are separate flows. The inclinations of -62.9° ± 3.1° for flow 10A in TAN CH#2 and -50.2° ± 3.9° for flow 10B in TAN CH#1 are significantly different. The ages of 1.412 ± 0.047 Ma for flow 10A and 1.581 ± 0.057 Ma for flow 10B are also significantly different.

The sedimentary interbed below flows 10A and 10B represents a major hiatus of eruptive activity in the TAN area. In TAN CH#2, flow 11 is approximately 600,000 years older than flow 10A, and, in TAN CH#1, flow 13 is about 350,000 years older than flow 10B. The ages of flow 11 in TAN CH#2 and flow 13 in TAN CH#1 agree within analytical uncertainty; there is no stratigraphic discrepancy. The age of 2.115 ± 0.046 Ma for flow 14 in TAN CH#2 suggests that the age of basalt lava at the bottom of TAN CH#1 is slightly more than 2 Ma.

The sedimentary interbed between flows 16 and 17 in TAN CH#2 also represents a significant hiatus in basalt eruption. The shift in inclination between flows 16 and 17 is about 16°. The ages of flows 14 and 17 in TAN CH#2 indicate that eruption of flows 15 and 16 and development of the interbed between flows 16 and 17 occurred during a period of more than 400,000 years. Flow 17 is at the top of a flow sequence having mean inclination values in the low -50°'s and flow 16 is at the base of a flow sequence having inclination values in the high -60°'s. From this, we infer that the hiatus occurs within the sedimentary interbed.

Flows 17 through 21 in TAN CH#2 have similar inclinations and ages. The analytical uncertainties in ages measured on flows 17 and 19 do not quite overlap; the age of flow 19 is younger than the age of the overlying flow 17. A reasonable interpretation is that the five flows, 17 through 21, were erupted about 2.5 Ma.

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APPENDIX A: Petrographic descriptions

Summary of petrographic characteristics

Basalt lava flows were sampled for thin section analysis at appropriate intervals. Samples were taken within flows to represent the top. ,middle, and bottom, and also to represent various textural varieties of the flow. Thin sections were studied by standard petrographic methods.

Basaltic lava flows of the Snake River Plain are remarkably similar to one another in terms of gross petrographic characteristics. Olivine, plagioclase, clinopyroxene, titanomagnetite, and ilmenite are the major mineral phases, apatite is rare. Nearly all thin sections examined are bimodal in terms of crystal size distribution; larger crystals of olivine, plagioclase, and rarely clinopyroxene, are set in a groundmass of these same minerals plus ilmenite and titanomagnetite. The larger crystals are typically 1-3 mm in longest dimension. Crystals constituting the groundmass are typically <0.5 mm.

Most flows are hypocrystalline but some are holocrystalline. Glass free of inclusions of equant opaque minerals and/or translucent minerals is extremely rare in Snake River Plain basalt flows. typically, the glass contains small areas of pinkish-tan clinopyroxene and discrete microlites of opaque minerals that are mostly <0.5 mm in longest dimension. The glass is mainly intersertal in most samples and rarely it occurs as a lining on vesicle walls.

Common textures are microporphyritic-porphyritic, glomerophyric, and diktytaxitic. Microporphyritic rocks contain larger crystals ~1 mm in a groundmass consisting of crystals typically <0.5 mm; porphyritic rocks contain larger crystals 1-3 mm in a groundmass containing crystals typically <0.5 mm. Many basalt flows are glomerophyric, containing clots of 2 or 3 to as many as 20 olivine crystals. Rarely the clots consist of olivine and plagioclase crystals. Open spaces in diktytaxitic rocks are mostly <1 mm. A rare but distinctive texture observed in some flows is here termed "starburst" texture, a special type of glomerophyric texture. This term describes clots of plagioclase or plagioclase+olivine crystals that appear to approximately radiate from a crystallization center. another distinctive texture, here termed "waist" texture, has plagioclase crystals radiating upward and downward, but not to the side, of a central olivine crystal.

Large olivines, 0.5-3 mm, are typically euhedral and less commonly subhedral. Some crystals are skeletal and contain irregular-shaped inclusions of glass. Nearly all large olivines contain inclusions of opaque and translucent minerals. The opaque inclusions are typically <0.05 mm, equant, and 4-sided, suggesting that they are of the titanomagnetite-ulvospinel series. The translucent inclusions are <0.05 mm, dark brown to cinnamon brown, and equant to rounded, suggesting that they are chromian spinel.

Plagioclase crystals are lath-shaped and have typical length:width ratios of 6:1 to 12:1. Crystals having length:width ratios less than 6:1 are termed "stubby" in these descriptions. Most plagioclase crystals show little or no evidence of zoning, but some show complex zoning relationships and inclusions of glass, olivine, and pyroxene. Phenocrysts of plagioclase and glomerophyric clots of plagioclase are rare in the thin sections examined. Plagioclase crystals of the groundmass in most rocks are stubby. Trachytic texture formed by aligned plagioclase crystals is common

Flow 1 (23.4' thick, 43.6' to 70.0'-TAN CH#1; 27.2' thick, 47.3' to 74.5', TAN CH#2).

Flow 1 is dark gray (2.5YR/4/0) in the upper and middle parts and dark gray (5YR/4/1) in the lower 5' in TAN CH#1. The flow is dark gray (2.5YR/4/0) in all parts in TAN CH#2. The upper 5-10' are vesicular, most vesicles are <10 cm and some are coated by calcite and caliche The bottom 1-5' contains vesicles <3 cm, some of which are coated by caliche. A 7'-thick massive layer is present just above the base of the flow in TAN CH#2 Flow-unit breaks at 55.5' and 62.9' were recognized in TAN CH#1 The flow consists of a single flow unit in TAN CH#2. The rock is not cindery at the top or base in either corehole, but the base of the middle flow unit is cindery in TAN CH#1. In hand sample, the rock is partly diktytaxitic and distinctly porphyritic, containing abundant plagioclase laths as long as 10 mm.

The texture of Flow 1 is distinctive. The rock is porphyritic, containing conspicuous crystals of plagioclase typically 4-7 mm long and a few olivine crystals as large as 1 mm diameter. The groundmass of the rock typically contains olivine and plagioclase crystals <5 mm. The rock is also glomerophyric, containing clots of olivine+plagioclase, only olivine crystals, and only plagioclase crystals Olivine crystals are euhedral to subhedral, roughly equant and as large as 1 mm Olivine crystals in the groundmass are <0.5 mm. The olivine contains euhedral crystals of opaque minerals that are <0.05 mm. Plagioclase crystals are typically stubby in shape and synneusis and cross-shaped twins are common in the upper parts of the flow. Most large crystals are 3-7 mm long and crystals in the groundmass are mostly <2 mm. Glass and olivine inclusions are common. Clinopyroxene crystals are only in the groundmass The crystals are typically anhedral, intergranular and <0.4 mm. A fair amount of intergranular brown glass is charged with dusty opaque minerals and tiny blades and needles of clinopyroxene. Needles of ilmenite <1 mm and patches (1-1.5 mm) of equant magnetite crystals, each of which is <0.2 mm diameter, are common. Interestingly, magnetite exceeds ilmenite in TAN CH#1 and ilmenite exceeds magnetite in TAN CH#2, based on microscopic estimates, but not accurate point counts.

Flow 2 (37.7' thick, 70.0' to 107.7' in TAN CH#1; 59.9' thick, 74.5' to 134.4' in TAN CH#2)

Flow 1 and flow 2 are not separated by a sedimentary interbed

Flow 2 is very dark gray (5YR/3/1 and 2.5YR/3/0) in the upper and lower 2/5 and dark gray (2.4YR/4/0) in the middle 1/5 in TAN CH#1. In TAN CH#2, flow 2 is weak red (10R/4/2) in the upper several feet, and weak red (10R/5/2 and dark reddish gray (10R/3/1) in the lower 10 feet In the middle, flow 2 is very dark gray (5YR/3/1), dark gray (2.5YR/4/0) and gray (2.5YR/5/0) in TAN CH#2. The more reddish, oxidized character of flow 2 in TAN CH#2 may be due to the fact that it lies closer to the vent than flows in TAN CH#1. This factor is amplified by the greater thickness of flow 2 in TAN CH#2 than in TAN CH#1. The upper 6' of flow 2 is vesicular in both coreholes and vesicles are <3 mm in TAN CH#2 and <10 mm in TAN CH#1. Calcareous clay coats some vesicles and loess-filled joints are present in TAN CH#1 about 6' below the top of the flow The middle parts of the flow are mainly massive in both coreholes and vesicular again only in the bottom 2-4'. Flow unit breaks are recognized at 89.9' and 99' in TAN CH#1 and at 92', 102' and 123.5' in TAN CH#2. In hand specimen, the rock is partly diktytaxitic throughout, and porphyritic to microporphyritic in TAN CH#1, where plagioclase crystals range from 10 mm near the top of the flow to about 2 mm at the base. In TAN CH#2, plagioclase is <2 mm throughout the flow. Olivine is <2 mm in both coreholes

In thin section, the rock is characterized by an equigranular texture. The rock is distinctly diktytaxitic in the upper parts but is not diktytaxitic in the lower 15'. Olivine crystals are granular, equant, anhedral to subhedral, typically <1 mm, and opaque inclusions are more common than translucent inclusions. Plagioclase crystals are <1.8 mm in the middle of the flow and typically <1 mm elsewhere. Some plagioclase crystals are strongly zoned and starburst clots of plagioclase crystals are rare. Clinopyroxene is <0.7 mm, intergranular to partly subophitic and anhedral. Glass is fairly common, brown in color, typically intersertal but also in clots to 3 mm , and charged with fine opaque minerals. Blades and needles of ilmenite are <0.6 mm, equant crystals of magnetite are typically <0.2 mm but also in clots of equant crystals <0.8 mm. Magnetite equals or exceeds ilmenite Alteration is very slight; a few olivine crystals contain iddingsite on fractures and cleavages.

Flow 3 (34.3' thick, 103.7 to 138' in TAN CH#1; 24.1' thick, 134.4' to 158.5' in TAN CH#2)

There is no sedimentary interbed between flow 3 and flow 2 in either of the two coreholes.

Flow 3 is very dark gray (2.5YR/3/0) at the top and at the bottom (5YR/3/1) and dark gray (2.5YR/4/0) in the middle in TAN CH#1. In TAN CH#2, flow 2 is dark reddish gray (10R/3/1) in the upper foot and dark gray (2.5YR/4/0 and 10YR/3/1) in the middle and lower parts.

In hand specimen, the rock is mainly fine grained, but locally is microporphyritic (felty) and contains plagioclase crystals <5 mm in a groundmass of other minerals <1 mm. The upper half of the flow is massive and non-diktytaxitic and the lower half is diktytaxitic. The upper 2' of the flow is massive in TAN CH#1 and vesicular in TAN CH#2, where it contains vesicles <20 cm, but most are <5 cm. The glass on walls of some vesicles is dark reddish brown (5YR/3/2). A flow-unit boundary occurs in Flow 3 at 141' in TAN CH#2; no flow-unit boundaries were recognized in TAN CH#1.

In thin section, the rock is characterized by even-grained, equigranular texture; locally the rock is microporphyritic and contains plagioclase crystals <2 mm in a groundmass of other crystals <1 mm. The rock is glomerophyric-olivine. Olivine crystals are equant, granular, <0.8 mm and typically <0.3 mm, and contain opaque>>transluscent inclusions that are <0.05 mm Plagioclase crystals are <2 mm and most are <0.8 mm. There is weak development of starburst texture and a few crystals contain complex twins. Pyroxene is intergranular at the top of the flow and grades downward into ophitic to subophitic texture at the base. The pyroxene possesses distinctive wavy extinction. Intersertal glass contains feathery, wispy opaques. Ilmenite needles are <0.5 mm and magnetite granules are <0.3 mm. Magnetite is equal to or exceeds ilmenite. The flow is only slightly altered; olivine crystals contain weak iddingsite coatings on fractures and cleavages near the base of the flow.

Flow 4 (47.5' thick, 138' to 185.5' in TAN CH#1; 65.5' thick, 158.5' to 224' in TAN CH#2).

There is no sedimentary interbed between flow 3 and flow 4.

Flow 4 is very dark gray (2.5YR/3/0, 5YR/3/1) and dark gray (5YR/4/1, 2.5YR/4/0) throughout most of its thickness in both coreholes. It is not oxidized at either top or bottom. The upper 7' of the flow is vesicular in both coreholes; oblong vesicles are as large as 10x20 cm, but most are spherical and <10 cm. A few vesicles are coated by calcareous clay. The bottom 1' in TAN CH#1 and the bottom 8' in TAN CH#2 are vesicular; vesicles sizes are similar to those in the vesicular part at the top of the flow and some vesicles are coated by calcareous clay. The middle 38' in TAN CH#1 and the middle 50.5' in TAN CH#2 are massive and partly diktytaxitic. Joints coated by calcareous clay occur at a depth of 12' in TAN CH#1 and at a depth of 35' in TAN CH#2. Flow 4 consists of a single flow unit in TAN CH#1 and 3 flow units in TAN CH#2, with flow-unit boundaries at 173' and 215.5'.

In hand specimen, the rock is typically fine grained, felty at the top of the flow, dense in the massive sections, and most minerals are <1 mm, but olivine crystals <2 mm are rare to moderate in abundance in the middle and lower parts of the flow in TAN CH#1.

In thin section, the rock is characterized by a fine-grained, granular, non-porphyritic texture and local glomerophyric clots of olivine. Olivine crystals are <0.8 mm and most are <0.4 mm, granular, subhedral to euhedral and contain small, equant opaque inclusions <0.05 mm. Plagioclase laths are <1.0 mm and most are <0.4 mm. Clinopyroxene is intergranular and <0.8 mm at the top of the flow and subophitic to ophitic and <1.6 mm in the middle and at the bottom of the flow. All crystals are anhedral and possess wavy extinction. Glass occurs as intersertal patches <2 mm that are charged with fine opaque minerals. Ilmenite needles are <0.8 mm, magnetite euhedra are <0.4 mm, and magnetite equals or exceeds ilmenite. Olivine crystals near the top of the flow have reddish-orange alteration on fractures and cleavages but the rock is essentially unaltered in its middle and lower parts.

Flow 5: (39.8' thick, 185.5 to 225.3' in TAN CH#1; 15' thick, 224' to 239' in TAN CH#2)

There is no sedimentary interbed between flow 4 and flow 5.

At the top, flow 5 is very dark gray (5YR/3/1) in TAN CH#1 and is dark reddish gray (10R/4/1) throughout its depth in TAN CH#2. The flow is dark gray (5YR/3/1, 2.5YR/4/0) throughout the rest of its depth in TAN CH#1.

The flow is not cindery at its top in either corehole but is cindery in the lowest 3" in TAN CH#1. The flow is vesicular in the upper 6' in both coreholes and vesicles are typically spherical and <10 cm. Most vesicles contain oxidized, reddened glass and vesicles are coated by calcareous clay in both coreholes. The flow consists of a single flow unit in both coreholes

In hand specimen, the rock is typically fine-grained, but locally felty, containing plagioclase crystals <2 mm, in TAN CH#1. The rock is diktytaxitic throughout its depth.

In thin section, the rock is characterized by a fine-grained, non-porphyritic texture, diktytaxitic texture throughout, and local glomerophyric clots of 2-6 olivine crystals. Olivine crystals are typically subhedral to euhedral, as large as 1.6 mm diameter in the middle of the flow, but <0.6 mm at the top and bottom of the flow; they contain glass and opaque inclusions <0.05 mm. The largest plagioclase crystals are as long as 3.2 mm in the middle of the flow and <2 mm in the top and bottom of the flow. Most crystals in the groundmass are <0.4 mm. Some plagioclase crystals are arranged in a swallowtail pattern and some contain glass inclusions at the top of the flow. Clinopyroxene is intergranular, <0.8 mm, and has wavy extinction throughout the flow. Patches of brown glass as much as 5 mm diameter are abundant at the top of the flow, but clinopyroxene is <0.5 mm and intersertal near the bottom of the flow. Ilmenite needles as long as 2.5 mm occur at the top of the flow and grade downward into needles typically <0.7 mm. Magnetite euhedra are <0.3 mm and ilmenite exceeds or is equal to magnetite throughout the flow. Films of iddingsite are on the surface of olivine crystals near the top of the flow and olivine crystals in the middle and bottom of the flow contain small amounts of iddingsite in fractures and cleavages.

Flow 6: (63.5' thick, 225.5' to 289' in TAN CH#1; 58' thick, 247' to 305' in TAN CH#2).

Flow 5 and flow 6 are not separated by a sedimentary interbed in TAN CH#1, but are separated by an 8'-thick sedimentary interbed in TAN CH#2. The interbed consists of fine sand and silt throughout and is oxidized to pink (7.5YR/7/4) at the top and light reddish brown (5YR/6/4) at the base. The composition of the interbed suggests that the sediment is of eolian origin.

In TAN CH#1, flow 6 is very dark gray ((7.5YR/3/0, 5YR/3/1) at the top and grades downward into dark gray (5YR/4/1, 2.5YR/4/0, 2.5YR/5/0) throughout most of the flow. Flow 6 consists of 5 flow units in TAN CH#1, having flow-unit boundaries at 245', 256', 259', and 278.5'. The flow is locally cindery and dark red (10R/3/6) and dark reddish gray (10R/4/1, 10R/3/1) immediately below flow-unit boundaries. In TAN CH#2, flow 6 is very dark gray (5YR/3/1) at the top and grades downward into dark gray (2.5YR/4/0) and gray (2.5YR/5/0) in the middle and lower parts. Flow 6 consists of 5 flow units in TAN CH#2 with flow-unit boundaries at 257', 271', 273.5', and 277'. The rock is dark reddish gray (10R/4/1) just below the flow unit break at 273.5', but gray and dark gray below the other flow-unit boundaries

In TAN CH#1, the flow is vesicular in the top 8' and contains vesicles as large as 15 cm, some of which are coated or filled by caliche. The middle of the flow is characterized by alternating zones, 4-20' thick, of massive and vesicular rock. Vesicles in these vesicular zones are typically spherical, <3 mm diameter, and some are filled or coated by calcite and/or calcareous clay. The flow is partly to weakly diktytaxitic throughout. In TAN CH#2, the flow units consist of vesicular rock that constitutes about half the thickness of each of the thicker flow units. Vesicles are <2 cm in all vesicular layers and vesicles locally contain calcite and calcareous clay coatings and partial fillings in the upper and middle parts of the flow. The massive parts of the thicker flow units are dense to diktytaxitic.

In hand specimen, the rock is typically fine-grained and contains crystals <1 mm. Moderate amounts of olivine crystals <1 mm are observed in the massive layers. Much of the rock in both coreholes is felty and plagioclase crystals are mostly <2 mm.

In thin section, the rock is even-grained and slightly glomerophyric, containing clots of 3-7 olivine crystals. The rock is typically diktytaxitic and not porphyritic. However, the flow contains phenocrysts of olivine (0.6-0.8 mm) and plagioclase (1-2.4 mm) in the upper 10' in TAN CH#2. Olivine crystals are as large as 1 mm in the middle of the flow and <0.6 mm at the top and bottom. Equant opaque and glass inclusions <0.07 mm are common. Plagioclase crystals are as long as 1.6 mm in the middle of the flow but typically <0.6 mm at the top and bottom. Clinopyroxene is intergranular and confined to the groundmass of the rock at the top of the flow and subophitic in the middle and bottom of the flow. All clinopyroxene is <0.6 mm and has wavy extinction. Glass is altered to opaque minerals and pyroxene in the upper 5' of the flow and intersertal in the lower part. Ilmenite needles as long as 1 mm occur near the upper part of the flow but are <0.6 mm in the middle and bottom of the flow. Equant magnetite crystals are <0.4 mm throughout the flow and magnetite is approximately equal to ilmenite.

Flow 7: (50' thick, 289' to 339' in TAN CH#1; 25' thick, 305' to 330' in TAN CH#2)

Flows 6 and 7 are not separated by a sedimentary interbed in TAN CH#1 or TAN CH#2.

Flow 7 is oxidized to dark reddish brown (5YR/3/2) at the top in TAN CH#1. The top of flow 7 is very dark gray (5YR/3/1) in TAN CH#2 and was not oxidized. The remainder of the flow is very dark gray (5YR/3/1), dark gray (5YR/4/1, 2.5YR/4/0) and gray (2.5YR/5/0). Flow 7 consists of 2 flow units in TAN CH#1 with a flow-unit boundary at 311.5', and it consists of a single flow unit in TAN CH#2. Flow 7 is very dark gray (5YR/3/1) in its upper half and gray (2.5YR/5/0) in its lower half in TAN CH#2.

The upper part of flow 7 in TAN CH#1 is vesicular for 9' below the top and contains vesicles <30 cm diameter but most are <5 cm. Many of the vesicles are filled or partly filled by caliche. The upper 15' of flow 7 in TAN CH#2 is vesicular, vesicles are <2 cm and lack coatings or fillings. The lower 10' of flow 7 is massive, diktytaxitic, and very crystalline in TAN CH#2.

In thin section, the flow is microporphyritic, containing olivine crystals <1.6 mm and plagioclase crystals <2.4 mm in a groundmass of the same minerals plus pyroxene that is typically <0.6 mm. Glomerophyric clots of 3-4 olivine crystals are present throughout the flow except in the lower 8-10'. Olivine crystals are mostly euhedral and contain inclusions of equant opaque minerals <0.07 mm and inclusions of translucent brown minerals <0.05 mm. Plagioclase laths are <1.2 mm in TAN CH#1. In TAN CH#2, plagioclase is <2.4 mm near the top of the flow and decreases to <1.2 mm near the bottom of the flow. Some plagioclase crystals contain complex twins near the bottom of the flow. Clinopyroxene is typically <1.6 mm, anhedral, and intergranular to subophitic. Ilmenite blades are as long as 1.5 mm in TAN CH#2 but decrease to <0.6 in the middle and bottom of the flow. Magnetite crystals are <0.4 mm and magnetite is equal to or exceeds ilmenite. There is very little glass in the flow except for patches <3 mm diameter that contain trellis ilmenite and spindles of pyroxene in the upper part of the flow in TAN CH#2. There is very little alteration in the flow; olivine crystals contain very small amounts of iddingsite

Flow 8: (13.5' thick, 339' to 352.5' in TAN CH#1; 15.5' thick, 330' to 345.5' in TAN CH#2).

Flow 7 and flow 8 are not separated by sedimentary interbeds in either TAN CH#1 or TAN CH#2.

Flow 8 is very dark gray (2.5YR/3/0, 5YR/3/1) at the top and bottom in TAN CH#1 and very dark gray (5YR/3/1) at the top and gray (2.5YR/5/0) at the bottom in TAN CH#2. Flow 8 consists of two flow units with a flow unit boundary at 345.8' in TAN CH#1. In that corehole, the cindery upper part of the lower flow unit is oxidized to weak red(2.5YR/4/2). Flow 8 consists of a single flow unit in TAN CH#2. The flow is vesicular for 3' at the top and for 7.5' at the bottom in TAN CH#1, where vesicles are <20 cm in longest dimension. In the upper vesicular layer, glass on vesicle walls is oxidized to dusky red (10R/3/3) Some of the vesicles are filled or partly filled by caliche in the upper vesicular layer and by calcite in the lower vesicular layer In TAN CH#2, the upper 11' of the flow is vesicular, vesicles are <2 cm and contain partial fillings of calcareous clay. Flow 8 is massive, diktytaxitic and sugary in texture in the lower 4' in TAN CH#2.

In hand specimen, the rock is typically microfelty and contains plagioclase crystals <2 mm and rare olivine crystals <3 mm in longest dimension

In thin section, the rock is mostly even-grained, diktytaxitic and most crystals are <1 mm. The rock contains a few clots, 1-2 mm, of glomerophyric olivine. Most olivine crystals are equant, euhedral, <0.4 mm, and contain a few equant opaque inclusions < 0.05 mm. Olivine crystals at the bottom of the flow are resorbed, embayed, skeletal, and spongy with plagioclase and opaque inclusions. The largest plagioclase crystals are 1.2 mm but most are in the groundmass, anhedral, and <0.4 mm. Clinopyroxene is mainly <1 mm, anhedral, intergranular to subophitic and locally has wavy extinction. Near the bottom of the flow, clinopyroxene is as large as 2.2 mm, subophitic to ophitic, very anhedral, and has wavy extinction. Brown glass is moderately abundant, intersertal, and charged with small opaque minerals and spindles of clinopyroxene. Ilmenite needles are <0.6 mm, magnetite euhedra are <0.5 mm and magnetite is approximately equal to ilmenite in abundance The flow is essentially unaltered.

Flow 9 (48.5' thick, 352.5 to 401' in TAN CH#1; 102.3' thick, 345.5 to 447.8' in TAN CH#2)

Flow 9 and flow 8 are not separated by sedimentary interbeds in either TAN CH#1 or TAN CH#2.

The top of flow 9 is cindery and weak red (2.5YR/4/2) in TAN CH#1 and weak red 10R/5/2) but not cindery in TAN CH#2 The remainder of the flow is black (5R/2/5/1), very dark gray (5YR/3/1, 2.5YR/3/0), dark gray (5YR/4/1), and gray (5YR/5/0, 2.5YR/5/0)

Flow 9 consists of 4 flow units in TAN CH#1 with flow-unit boundaries at 375', 386', and 390'

Flow 9 consists of 2 flow units in TAN CH#2, with a flow-unit boundary at 402'. The flow is vesicular in the upper 9' in both coreholes; vesicles as large as 20 cm are partly to completely filled by calcite. The remainder of the flow is mostly massive in both coreholes, except in TAN CH#1 where vesicular zones are present beneath most flow unit boundaries. Beneath the flow unit boundary at 375', the flow is vesicular, vesicles reach 40 cm in maximum dimension, and they are not filled by calcite. The rock is mainly diktytaxitic in massive sections and contains moderate to abundant olivine clots which are mostly <4 mm.

In thin section, the rock is characterized by olivine phenocrysts as large as 3.5 mm, and clots of glomerophyric olivine <4 mm in a diktytaxitic groundmass of olivine, plagioclase and pyroxene that are mostly < 1.5 mm. The olivine crystals are euhedral-subhedral and contain distinctive translucent, brown inclusions, as well as equant opaque inclusions, that are <0.075 mm. Olivine crystals in the groundmass are typically <0.4 mm. Plagioclase crystals are anhedral, <0.6 and most crystals are <0.3 mm. Clinopyroxene crystals are <2 mm at the top and middle of the flow where they are intersertal to subophitic and have wavy extinction. In the bottom 1/3 of the flow, pyroxene is <1 mm or absent and replaced by glass with incipient clinopyroxene spindles. There is a little brown, intersertal glass at the top and in the middle of the flow and the amount of glass increases sharply in the bottom 1/3 of the flow, where it is brown and filled with opaque and tiny pyroxene crystals. Ilmenite blades are typically <0.4 mm and equant magnetite crystals are as large as 1.5 mm at the top of the flow and decrease to <0.3 mm at the bottom of the flow. Alteration of the flow is moderate at the top and bottom and only slight in the middle of the flow. Both olivine and pyroxene crystals are coated by opaque minerals and cracks are filled by iddingsite where alteration is strongest.

<u>Flow 10</u> (31.3' thick, 412 to 443.3' in TAN CH#1, 16.6' thick, 452.4 to 469' in TAN CH#2.)

Flow 9 and flow 10 are separated by a sedimentary interbed in both coreholes. The interbed is 11' thick and extends from 401' to 412' in TAN CH#1. In TAN CH#2, the interbed is 4.4' thick and extends from 447.9' to 452.3'. In both coreholes, the sediment is fine sand and silt, presumably of eolian origin. The interbed is light reddish gray (5YR/6/4) at the top and grades downward to pinkish gray (7.5YR/7/2) at the base in TAN CH#1 and it is pink (7.5YR/7/4) throughout in TAN CH#2

The top 8' and the bottom 1' of flow 10 are vesicular in both coreholes. At the top, vesicles are <10 cm in TAN CH#1 and <1 cm in TAN CH#2. At the top of the flow in TAN CH#1, the vesicles contain some coatings and complete fillings by caliche, calcite, and noncalcareous reddish yellow (5YR/6/8) clay. In both coreholes, fractures and joints at the base of the vesicular zone are filled by light brownish gray (10YR/6/2) fine sand and clay. The middle 22.3' in TAN CH#1 and 8.5' in TAN CH#2 are massive and diktytaxitic. In the middle of the massive zone in TAN CH#2, fractures are filled by noncalcareous, yellowish brown (10YR/5/6) fine sand and clay. The flow consists of a single flow unit in TAN CH#2 and perhaps two flow units in TAN CH#1, with a flow unit boundary at approximately 418-420'. At that depth, a significant amount of reddish-yellow (10YR/6/2) loess in fractured basalt may represent a thin sedimentary interbed. In hand specimen, the rock is typically fine-grained, but locally contains plagioclase and olivine crystals <2 mm

In thin section, the rock is characterized by a coarse texture in which olivine, pyroxene and plagioclase are all <3 mm but typically >0.6 mm. Olivine is glomerophyric , subhedral to euhedral, contains few opaque or translucent inclusions and is <1 mm in TAN CH#1 and <2 mm in TAN CH#2 Plagioclase crystals 1-3 mm are complex, containing several complexly-twinned, strongly-zoned crystals. Most crystals are >0.8 mm. Pyroxene crystals are typically 0.5-2 mm, intergranular to subophitic and anhedral. There is considerable intersertal brown glass charged with opaque minerals at the top of the flow and lesser amounts of similar glass at the bottom of the flow Ilmenite blades and equant magnetite crystals are both <0.5 mm and ilmenite is equal to or exceeds magnetite.

Flow 11: (75.3' thick, 473' to 548.3' in TAN CH#2 only)

A 4'-thick sedimentary interbed extending form 469' to 473' separates flow 11 and flow 10 in TAN CH#2 The interbed consists of pinkish gray (7.5YR/7/2) fine pebble gravel in which there are pebbles and granules of basalt and quartzite <2 cm in a groundmass of calcareous sand at the top, which grades downward into pinkish white (7.5YR/8/2) sand at the bottom The grain size and composition of the interbed suggests that it is of fluvial origin

Flow 11 consists of 3 flow units; flow-unit boundaries are at 484' and 536'.

The flow is very dark gray (5YR/3/1) at the top and gray (5YR/5/1) in the middle. The flow takes on a reddish hue in some of its middle and lower parts, where it is dark reddish gray (10R/4/1), weak red (10R/4/2), and dark red (10R/3/6) below the flow unit boundary at 536'.

The flow is vesicular for 27' below the top and vesicles are typically <1 cm diameter. A few of the vesicles are coated or filled by calcareous clay. The remaining 50' of the flow is an alternation of vesicular and massive layers that range from 4' to 15' in thickness. Massive layers are typically diktytaxitic and olivine and plagioclase crystals <4 mm are rare to moderate in abundance. The vesicular layers contain vesicles <5 cm and most are not filled

Rock in flow 11 is distinctive in texture, it has a strongly porphyritic appearance, containing olivine and plagioclase phenocrysts in a very fine-grained groundmass in the upper and middle parts It is glomerophyric-olivine and porphyritic-plagioclase at the bottom. Olivine and plagioclase crystals are not that large (olivine <1.5 mm, plagioclase <2.5 mm), but they appear distinctively large because they lie in a groundmass of crystals that are typically <0.6 mm.

Olivine occurs as euhedral phenocrysts that are as large as 1.2 mm at the top and 1.5 mm at the bottom of the flow. Most crystals are 0.8-1.0 mm and <0.4 mm in the groundmass. Olivine appears to contain few opaque or translucent inclusions. Olivine phenocrysts are <1.6 mm at the top, <2.5 mm in the middle, and <2.2 mm at the base of the flow. Many crystals are equant and square in outline and contain complex twins and complex zoning patterns Plagioclase crystals in the groundmass are typically <0.8 mm. Clinopyroxene is <0.3, anhedral, and intergranular at the top of the flow but 0.8-1.2 mm and intergranular to subophitic at the base The clinopyroxene has wavy extinction in larger crystals There is much intersertal brown glass at the top of the flow and lesser amounts in the middle and lower parts The glass is typically charged with fine opaque minerals and spindles of clinopyroxene. Needles of ilmenite and equant magnetite crystals are <0.2 mm at the top and increase to 0.4-0.8 mm near the bottom Ilmenite ≥magnetite. There is moderate to weak alteration in the flow expressed by coats of opaque minerals and iddingsite on the surfaces and in cleavages and fractures of olivine crystals.

Flow 12: (57.5' thick, 448' to 505.5' in TAN CH#1 only.)

Flow 12 and flow 10 are separated by a 4.5'-thick sedimentary interbed that extends from 443.5' to 448'. The interbed is fine sand and silt throughout that is red (2.5YR/5/6) at the top, reddish yellow (7.5YR/6/4) in the middle and pinkish gray (7.5YR/7/2) at the base The uniform grain size in the interbed suggests that it is loess of eolian origin

Flow 12 consists of 4 flow units with flow-unit boundaries at 453.5',477.5' and 491'.

The flow is very dark gray (2.5YR/3/1) and vesicular at the top. The vesicles are coated by pale brown (10YR/6/3) clay The flow changes to weak red (2.5YR/4/2) about 6' below the top From there downward, the flow is dark gray (2.5YR/4/0, 5YR/4/1) to very dark gray (5YR/3/1). Glass in the rock below the 477.5' flow-unit boundary is dusky red (2.5YR/3/2) and vesicle walls are dark reddish gray (5YR/3/2) below the 491' flow-unit boundary.

The flow is vesicular in the upper 9' and vesicles are all <10 cm in diameter and partly to wholly filled by calcareous clay From there downward, the flow is an alternation of 8 massive and vesicular layers that range from 2' to 10' thick. In the lower part of the flow, vesicles are as large as 20 cm and they are not filled In hand specimen, the rock is strongly diktytaxitic in massive layers, fine-grained and contains rare plagioclase crystals <2 mm.

In thin section, the rock is fine-grained, even-grained and characterized by relatively small olivine crystals The rock is slightly porphyritic in the middle where plagioclase crystals reach nearly 2 mm. Subhedral olivine crystals are <0.4 mm at the top and bottom and reach 1.6 mm in the middle of the flow. Plagioclase crystals are 1.2 mm at the top, 1.8 mm in the middle and most are <0.4 mm in the groundmass. The crystals are mainly intergranular and plagioclase at the bottom of the flow contains complex twinning and zoning Intergranular clinopyroxene is <1.5 mm at the top and grades downward into intergranular-subophitic crystals <0.4 mm at the bottom Glass is minor in amount throughout the flow, intersertal and charged with opaque minerals and incipient clinopyroxene crystals Ilmenite needles and blades are <0.4 mm, magnetite euhedra are <0.2 mm, and magnetite=ilmenite The flow is moderately altered throughout where olivine crystals are coated by iddingsite and minor opaque minerals

Flow 13: (38' thick, 505.5' to 543.5' in TAN CH#1 35.5' thick, 548.5' to 584' in TAN CH#2)

Flow 13 is not separated by a sedimentary interbed from flow 12 in TAN CH#1 and it is not separated by a sedimentary interbed from flow 11 in TAN CH#2.

Flow 13 consists of a single flow unit in TAN CH#1 and perhaps two flow units in TAN CH#2, where there is a possible flow-unit boundary at 564'.

Flow 13 is mainly vesicular in TAN CH#2, the top 8' and the bottom 25' are vesicular and a 3'-thick massive layer lies between. In TAN CH#1, the top 17' are vesicular, the next 15' are massive and then there are alternate beds of massive and vesicular rock 1-6' thick. Flow 13 has a distinctive reddish tinge in TAN CH#2; the flow is dusky red (10R/3/6) at the top , dark reddish gray (10R/4/1) in the middle, and weak red (10R/4/1) at the bottom . Flow 13 in TAN CH#1 is dark reddish brown (5YR/3/2) at the top and then dark gray (5YR/4/1) and gray (5YR/5/1) in the lower 85% of the flow. In the top vesicular layer in TAN CH#1, vesicles are <5 cm at the top and as large as 50 cm 8' below the top, where there are thin films of caliche that line the vesicle walls. Vesicles are <5 cm in the lower layers. In TAN CH#2, vesicles are <5 cm at the top and <1 cm at the bottom. The vesicles are partly filled by calcite in the upper vesicular zone.

In hand specimen, the rock is very fine-grained and all minerals are <1 mm long. The rock is very dense in massive layers and weakly diktytaxitic in vesicular layers and strongly diktytaxitic in massive layers.

In thin section, the rock is characterized by a lack of distinctive textural features; the rock is very fine-grained, it is not porphyritic and it is not glomerophyric. Olivine crystals are typically rare in the rock and <0.2 mm at the top, <0.4 mm in the middle and <0.6 mm at the bottom in TAN CH#1. In TAN CH#2, the olivines are <0.5 mm at the top and <0.15 mm at the bottom. Plagioclase crystals are <0.6 mm in both coreholes, equant at the top and long-slender near the bottom. They are quite strongly zoned but not complexly twinned. Clinopyroxene occurs as tiny anhedral crystals at the top, subophitic crystals <0.8 mm in the middle, and intergranular to subophitic crystals <0.4 mm at the bottom. There is very little glass in the flow. Ilmenite and magnetite are both <0.2 mm. There is little alteration at the top of the flow, but alteration increases to moderate at the middle and bottom, where olivine crystals are slightly coated by iddingsite.

Flow 14: (Minimum of 56.5', 543.5 to 600[total depth] in TAN CH#1; 60' thick, 586' to 646' in TAN CH#2)

Flow 14 is not separated from flow 13 by a sedimentary interbed in TAN CH#1, but is separated by a 2'-thick interbed in TAN CH#2. The interbed is weak red (7.5YR/7/2) fine sand and silt, presumably of eolian origin.

Flow 13 consists of a single flow unit in TAN CH#2 and consists of 3 flow units with flow-unit boundaries at 573.5' and 588' in TAN CH#1.

Flow 13 contains 10.5' of vesicular rock at the top in TAN CH#2 and is mainly massive in the lower 50'. The vesicles are <1 cm and filled by calcareous clay. The vesicular top of the flow is weak red (10R/4/2) and the flow grades downward into dark gray ((2.5YR/4/0) in the massive layer. Nearly vertical joints filled by white (10YR/8/2) fine sand and silt are common in the rock in the interval 600-615'.

In TAN CH#1, the rock is weak red (2.5YR/4/2) at the top and then grades downward into very dark gray (5YR/3/1), dark gray (5YR/4/1) and gray (5YR/3/1) rock, except just below the flow-unit boundaries, where the rock is weak red (2.5YR/4/2) and dusky red (2.5YR/3/2). The top 20' of the flow is vesicular and contains vesicles as large as 5x30 cm, but most vesicles are nearly spherical and <10 cm diameter. The vesicles are free of calcareous filling material or contain very thin films of caliche. Below the thick vesicular top of the flow are alternating layers of vesicular and massive rock that are 5 to 10' thick. The massive layers are very dense and not particularly diktytaxitic. The vesicular layers contain vesicles as large as 15x50 cm, some of which are completely or partly filled by calcareous clay or calcite.

In hand specimen. the rock is distinctly fine-grained and all crystals are <1 mm.

In thin section, rock at the top of the flow is characterized by a very fine texture with rare, small phenocrysts of olivine as large as 1.2 mm in a groundmass of minerals typically <0.4 mm. The rock becomes coarser grained toward the bottom as there the rock contains phenocrysts of olivine and plagioclase 1.5-2 mm long. Olivine is typically <0.6 mm at the top and as large as 1.2 mm at the base of the flow, where crystals have glass inclusions. Olivine crystals in the groundmass are <0.5 mm. Plagioclase crystals are 0.6 mm long at the top and increase to as large as 2 mm at the base of the flow. Plagioclase in the groundmass is <0.5 mm. Plagioclase is subhedral and the largest crystals are significantly zoned An unusual texture near the bottom of the flow involves odd-shaped patches of plagioclase that fill diktytaxitic void space. From top to bottom, clinopyroxene increases in size from 0.2 to 0.8 mm in TAN CH#1 and decreases in size from 1.8 mm to 0.6 mm in TAN CH#2. In TAN CH#1, the clinopyroxene is subhedral and mainly intergranular to subophitic and in TAN CH#2, it is anhedral and mainly ophitic to subophitic. Near the base of the flow In TAN CH#2, there are some large, single crystals that are not ophitic. Glass is essentially absent in flow 14. Ilmenite and magnetite are both <0.3 mm and magnetite exceeds ilmenite. There is moderate alteration of olivine throughout the flow and calcite is present in void spaces in the middle of the flow.

Flow 15: 53' thick, 646' to 699' in TAN CH#2)

Flow 15 and flow 14 are not separated by sedimentary interbed in TAN CH#2.

Flow 15 consists of 4 flow units with flow-unit boundaries at 654', 664', and 666'.

The upper 10' of flow 15 is vesicular and dark gray (5YR/4/1) at the top, gray (5YR/5/1) at a depth of 652', and dark gray (2.5YR/4/0) at a depth of 660'. The vesicles are <3 cm and most are <1 cm. They are partly to completely filled by calcareous clay and calcite only at the bottom of the top vesicular layer. Then follows 5' of massive rock, 11' of vesicular rock, 25' of massive rock and a lower 2' of vesicular rock. The rock below the upper vesicular zone is dark gray (2.5YR/4/0, 5YR/4/1) in the middle and gray

(2.5YR/5/0) near the bottom of the flow Rock in the 2'-thick layer between flow unit boundaries at 664' and 666' is weak red (10R/4/2) and the upper 2' of rock just below the 666' flow-unit boundary is rubbly and contains calcareous clay as cement between cobbles and pebbles In the thick massive layer, tiny calcite rhombs fill diktytaxitic openings and there are many vertical joints at about 685-688' that are coated or filled by calcite.

In hand specimen, the rock ranges from dense and diktytaxitic with all minerals <1 mm to porphyritic containing rare to moderate olivine and plagioclase crystals <3 mm.

In thin section, the rock is fine-grained and has a dense groundmass, olivine and plagioclase phenocrysts, and the rock is glomerophyric, containing clots of olivine, plagioclase and olivine+plagioclase Olivine crystals are <1.8 mm, subhedral to anhedral, they contain only a few opaque and translucent inclusions and crystals in the groundmass are typically <0.4 mm. Plagioclase crystals are <1.3 mm, but many crystals are in the 1.0-1.2 mm range and they are weakly zoned. Crystals in the groundmass are typically <0.4 mm. Clinopyroxene is anhedral, subophitic to ophitic and <1.2 mm The rock contains little or no glass. Both ilmenite and magnetite are <0.2 mm and magnetite exceeds ilmenite. Olivine is mostly fresh, but there are considerable amounts of calcite scattered through most specimens

Flow 16: (34' thick, 699' to 733' in TAN CH#2)

Flow 16 and flow 15 are not separated by as sedimentary interbed in TAN CH#2.

Flow 16 consists of a single flow unit

Flow 16 is vesicular for 8' at the top; vesicles are <3 cm, most are <1 cm, and they are filled by calcareous clay to a depth of 705'. The remaining 26' of the flow is mainly massive, partly diktytaxitic, and all minerals are <1 mm near the top. In the middle of the massive layer, plagioclase <3 mm is moderate to rare and olivine is <1.5 mm. The rock is coarsest at and near the bottom of the flow where moderate to abundant plagioclase and olivine are <3 mm. The flow is dark gray (2.5YR/4/0) and not reddened at the top and passes downward into very dark gray (5YR/3/1) rock in the middle and lower parts of the flow.

In thin section, the rock is weakly porphyritic at the top and strongly porphyritic in the middle and bottom In the middle, the groundmass is fine and dense and the rock contains both olivine and plagioclase phenocrysts The rock is glomerophyric and contains clots of olivine+plagioclase, but not clots of just olivine or just plagioclase Olivine is <1 2 mm, subhedral, contains few opaque inclusions and crystals in the groundmass are <0.2 mm Olivine increases to 1.8 mm near the bottom of the flow and many large crystals are in the 0.8-1 5 mm range. The crystals there are subhedral, partly skeletal and they contain inclusions of opaque minerals and glass. Olivine crystals in the groundmass in the bottom part are typically 0.2 mm. Plagioclase crystals are <1.6 mm in the middle and <2 0 mm at the bottom of the flow Plagioclase is subhedral, weakly zoned and crystals are mostly stubby. Crystals at the bottom of the flow are skeletal and have inclusions of glass Plagioclase in the groundmass is <0.4 mm. Clinopyroxene occurs as subhedral rounded, granular crystals that are intergranular and <0.2 mm throughout the flow. The flow contains abundant brown, opaque-free glass at the top of the flow and virtually no glass at the bottom of the flow. Ilmenite and magnetite crystals are <0.2 mm and magnetite exceeds ilmenite. At the top of the flow, olivine is altered to chrysotile(?). The flow is not altered at the base.

Flow 17: (134.5' thick, 742' to 876.5' in TAN CH#2)

Flow 17 is separated from flow 16 by a 9'-thick sedimentary interbed that extends from 733' to 742'. The interbed consists of fine sand throughout, suggesting that it is of eolian origin The interbed is reddish black (10R/2.5/1) at the top, white (10YR/8/2) just 1' below the top, pinkish gray (7.5YR/7/2) in the middle and pinkish gray (7.5YR/6/2) at the base.

Flow 17 is the most puzzling flow encountered in coreholes TAN CH#1 and TAN CH#2. The flow consists of 9 flow units with significant oxidation in the upper parts of 6 of these flow units, but all flow units have the same distinctive mineralogy and texture, This suggests that flow 17 is indeed 134.5' thick, but we recognize that there may be several separate flows within this interval

The flow unit breaks occur at the following depths and the colors of the flow at those depths are also given: 754' (reddish gray-10R/5/1), 760' (dark gray-5YR/4/1), 762' (dark gray-5YR/4/1), 796' (weak red-10R/4/2), 804' (dark reddish gray-10R/3/1), 821' (weak red-10R/4/2), 845.4' (dark reddish gray-10R/3/1), and 863' (dusky red-10R/3/2).

Flow unit 1 is vesicular in the upper 2', dark gray and massive in the middle and lower 9'. The vesicular zone is dark gray (2.5YR/4/0) and contains vesicles <2 cm that contain blobs or are filled by calcite The massive zone is gray (2.5YR/5/0) and strongly diktytaxitic. Flow unit 2 is vesicular in the upper 2', the vesicles are filled by calcite and the vesicular zone is reddish gray (10R/5/1). The bottom 4' of flow unit 2 is massive and contains joints filled by calcareous clay. Flow unit 3 is 2' thick, vesicular, and dark gray (5YR/4/1) Flow unit 4 is massive in its upper 31' and vesicular in the lower 4'. The massive zone is dark gray (5YR/4/1, 2.5YR/4/0) throughout, partly diktytaxitic and microfelty Joints filled by calcareous clay occur in the interval 780' to 785'. Flow unit 5 is vesicular in the upper 3', weak red (10R/4/2), vesicles are <2 cm, and calcite occurs as coats and fills in the vesicles. The middle 4' of the flow unit is massive and the lower 1' is vesicular. Flow unit 5 is also microfelty and contains olivine and plagioclase crystals <2 mm The upper 6' of flow unit 6 contains vesicles <1 cm in diameter that are partly filled by calcite in the upper 1'. The middle 10' of the flow unit is massive, microfelty and dark gray (2.5YR/4/0) and the lower 1' of the flow unit is vesicular and also dark gray Flow unit 7, 24' thick, consists of alternating vesicular and massive units that are 2' to 10' thick; the vesicles are typically <1 cm in diameter and locally contain calcite rhombs in the central part of the flow. Massive layers are typically gray (2.4YR/5/0) to dark gray (2.5YR/4/0), diktytaxitic and contain crystals <1 mm in diameter. The upper 7' of flow unit 8 is dark reddish gray (10R/3/1), vesicular (<3 cm diameter) and vesicles mostly lack mineral fillings. The middle 11' of the flow is massive, partly diktytaxitic, gray (2.5YR/5/0) and fine-grained, where all minerals are <1 mm in longest dimension. The lowest 1' of the flow unit is vesicular and vesicles are , <1 cm in diameter and free of mineral fillings. The upper 5.5' of flow unit 9 is vesicular, vesicles are <2 cm in diameter, and lack mineral fillings The lower 7' of the flow unit is massive and diktytaxitic

The mineralogy and texture of flow 17 is remarkably uniform in 7 thin sections from the flow The rock is "coarse-grained" relative to flows above and below and is distinctly non-porphyritic and non-glomerophyric in its middle parts. Most crystals in the rock are in the 0.5-1.5 mm range. The rock contains olivine phenocrysts as large as 1.4 mm only at the top, and the rock is glomerophyric-olivine only in the top and bottom of the flow. The rock is mainly subophitic and diktytaxitic throughout. Olivine crystals are typically subhedral, 0.2-0.6 mm and contain equant opaque inclusions <0.03 mm in diameter Plagioclase crystals are typically stubby and have seriate long dimensions in the range 2.0 to 0.2 mm Most crystals are distinctly zoned and contain glass inclusions. Pyroxene crystals are <1.2 mm, anhedral-subhedral, subophitic and locally strained. Brown intersertal glass that contains spindles of pyroxene crystals and dusty opaque minerals is present throughout the flow. Blades and needles of ilminite are <0.8 mm and equant crystals of magnetite are <0.6 mm Ilminite is equal to or slightly exceeds magnetite

Flow 18: (101' thick, 876.5 to 977 in TAN CH#2)

Flow 17 and flow 18 are not separated by a sedimentary interbed in TAN CH#2.

Flow 18 consists of 6 flow units with flow-unit boundaries at 923.5', 938.5', 964.5', 968.5' and 972 The uppermost flow unit is dark reddish gray (10R/3/1) and vesicular at the top. The vesicular zone is 10' thick and contains vesicles typically <1 cm at the top that are fairly free of fillings and vesicles as large as 5 cm at the bottom of the zone. About 3' below the top of the flow is a layer 6" thick in which vesicles are filled or partly filled by calcite rhombs Below the vesicular layer is a massive layer 36' thick that consists of dense, diktytaxitic rock that is gray (2.5YR/5/1) to dark gray (2.5YR/4/1). Joints near the middle of the massive layer are clean. The base of the flow unit is a 1'-thick vesicular layer. The second flow unit is dark reddish gray (10R/4/1) and vesicular in the upper 9' The vesicles are typically <1 cm and partly filled by calcite. The flow unit is massive in the lower 5', diktytaxitic and relatively coarse in crystal size. The third flow unit is dark reddish gray (10R/3/1) and vesicular in the upper 9'; vesicles are essentially free of filling material. The middle 16' of the flow unit is massive, dark gray (2.5YR/ 4/0), and diktytaxitic Vertical joints in the middle of the massive layer contain coatings of light greenish-brown alteration mineral(s), probably epidote. The lower 3 flow units are 3-5' thick, vesicular, slightly oxidized to pale red (10YR/6/4) and reddish gray (10YR/5/1), and contain vesicles that are filled by non-calcareous clay, calcareous clay, and calcite The bases of these flow units contain rock that is very dark gray (2.5YR/3/0) to dark gray (2.5YR/4/0).

In hand specimen, the rock is characterized by moderately abundant plagioclase <3 mm and olivine crystals <2 mm

In thin section, the rock is distinctly porphyritic throughout; olivine phenocrysts are prominent at the top and olivine + plagioclase phenocrysts are common near the bottom. The rock is glomerophyric-olivine throughout Olivine crystals are typically <1 mm at the top and increase to <1.6 mm near the middle of the flow and decrease to <1.4 mm at the base. The olivine crystals are subhedral and partly skeletal at the base of the flow Larger olivine crystals contain equant opaque mineral inclusions <0.03 mm and olivine crystals in the groundmass are typically <0.4 mm. Plagioclase crystals are <1.5 mm at the top and <2 5 mm in the middle and at the base of the flow The crystals are mostly stubby, contain glass inclusions in the middle and base of the flow, and are weakly zoned. Many crystals are 1-2 mm and plagioclase in the groundmass is <0.6 mm Clinopyroxene is <1.5 mm at the top and bottom and <2 2 mm in the middle of the flow. The crystals have wavy extinction, are invariably anhedral and subophitic at the top and bottom and ophitic in the middle There are minor amounts of brown glass throughout the flow. Needles and blades of ilmenite are <0.5 mm and equant crystals of magnetite are <0.4 mm. Magnetite equals or exceeds ilmenite The upper part of the flow is moderately altered; olivine crystals have orange-red coatings on outer surfaces and on cleavages and fractures. The base of the flow is essentially unaltered.

Flow 19: (51.5' thick, 981' to 1032 5.5' in TAN CH#2)

Flow 18 and flow 19 are separated by a 3'-thick sedimentary interbed in TAN CH#2 The interbed consists of reddish gray (10R/6/1) fine sand and silt of probable eolian origin

Flow 19 consists of 2 flow units with a flow unit boundary at 1022'. The upper flow unit is gray (5YR/5/1) and vesicular in the upper 12' The vesicles are mainly <1 cm but a few are as large as 5 cm The vesicles are thinly coated by yellow (10YR/8/6) material, probably zeolite minerals. The middle 27' of the flow unit is massive, diktytaxitic, and has a sugary texture Vertical joints at 1007' are not filled or coated by minerals. The lower 1.5' of the flow unit is vesicular and vertically jointed. The joints are filled by calcite. The lower flow unit is very dark gray (5YR/3/1) and vesicular in the upper 3.5'. The vesicles are <2 cm and some are filled by calcite. The lower 7' is massive, dark reddish gray (10R/4/1) and diktytaxitic

In hand specimen, the rock is felty and even-grained, giving the rock a sugary appearance A few plagioclase and olivine crystals <1 mm are evident in the lower flow unit.

In thin section, The rock is even-grained, not porphyritic, diktytaxitic, and contains small glomerophyric clots of several olivine crystals in the groundmass Olivine crystals are <0.7 mm, subhedral, and they contain equant opaque minerals <0.06 mm Plagioclase crystals are <1 mm throughout the flow and mainly <0.6 mm. The plagioclase crystals are anhedral and are not strongly zoned Clinopyroxene crystals are anhedral, blade-shaped, as large as 2.2 mm, and ophitic to subophitc at the top of the flow. Near the base of the flow, the crystals are more equant, <1.3 mm, anhedral and subophitic There is a fair amount of intersertal, weak brown glass that is charged by spindles of pyroxene and opaque minerals throughout the flow. Ilmenite blades are <0 7 mm and clots of equant magnetite crystals are <0.5 mm. Magnetite exceeds or is equal to ilmenite All olivine crystals in the flow are coated by iddingsite and much of the intersertal glass is recrystallized

Flow 20 (60.5' thick, 1032 5' to 1093' in TAN CH#2)

Flows 20 and 19 are not separated by a sedimentary interbed in TAN CH#2.

Flow 20 consists of 3 flow units with flow-unit boundaries at 1046' and 1053.5'. The upper flow unit is weak red ((10R/5/2) at the top and vesicular for 7'. The vesicles are <1 cm and contain scattered rhombs of calcite. The middle 3.5' is massive, dark gray (2.5YR/4/0) and diktytaxitic. The lower 2' contains vesicles <1 cm that are partly filled by calcite. The middle flow unit, 7' thick, consists of equal parts of vesicular rock at the top and massive rock at the bottom. The rock is dark gray (5YR/4/1). The lowest flow unit is vesicular for 12' at the top. The vesicles are <2 cm and about 10% of them are filled by calcite. The vesicular rock is dark gray (5YR/4/1). The remainder of the flow unit is mainly vesicular, but contains 3 massive layers that are <2' thick. The lower flow unit is mainly gray (5YR/5/1) at the top and dark gray (2.5YR/4/0) at the bottom. There are many joints between 1075' and 1080', most of which are partly or completely filled by calcite. The vesicular layer in the lower 5' of the flow unit contains much calcite

In hand specimen, the rock is mainly dense, containing crystals that are all <1 mm.

In thin section, the rock has distinctly diktytaxitic and contains olivine phenocrysts and glomerophyric clots of olivine. Olivine crystals are euhedral, <1.8 mm at the top and euhedral-subhedral and <1 mm at the bottom. The larger olivine crystals contain inclusions of euhedral opaque minerals <0.4 mm. Olivine crystals in the rock groundmass are <0 2 mm. Plagioclase crystals are 0 7 mm throughout the flow, anhedral and very weakly zoned. Pyroxene crystals are <1.7 mm throughout the flow, anhedral and subophitic There is little glass in the flow. Blades and needles of ilmenite are <0 5 mm, magnetite euhedra are <0.2 mm, and magnetite exceeds or is equal to ilmenite. Olivine crystals near the top of the flow have rims of iddingsite and calcite is widespread in diktytaxitic cavities and vesicles throughout the flow.

Flow 21: (Minimum thickness of 11.5', 1102 to 1113.5' [total depth] in TAN CH#2.

Flow 20 and flow 21 are separated by a 9.5' thick sedimentary interbed. The interbed is fine sand and silt that is filled with angular basalt cobbles and pebbles Material between the basalt fragments is calcareous clay and calcite in the upper and middle parts The interbed is mainly strong brown (7 5YR/5/6) The cement between basalt fragments at the base of the interbed is not calcareous.

Flow 21 consists of a single flow unit in the 11 5' penetrated in TAN CH#2. The rock is very dark gray and dense at the top The vesicular upper 5' consists of angular blocks having calcite cement Near the bottom of the hole, the flow consists of very angular black basalt Joints at this level are filled by calcite

The rock is dense and all minerals are <1 mm in hand specimen

In thin section, the rock is very fine grained, diktytaxitic, and contains phenocrysts of olivine and sparse glomerophyric clots of olivine The largest olivine crystals are <1 mm and most are <0 2 mm Most large crystals are euhedral; some smaller crystals are skeletal and contain glass inclusions. Plagioclase crystals are slender, <0 5 mm and weakly zoned clinopyroxene occurs as spindles and needles in the groundmass. There is extensive brown, intersertal glass that is filled with opaque minerals and small clinopyroxene crystals. Both magnetite and ilmenite are <0.1 mm and ilmenite exceeds magnetite Olivine is coated by iddingsite and there is much calcite in diktytaxitic cavities and in vesicles.

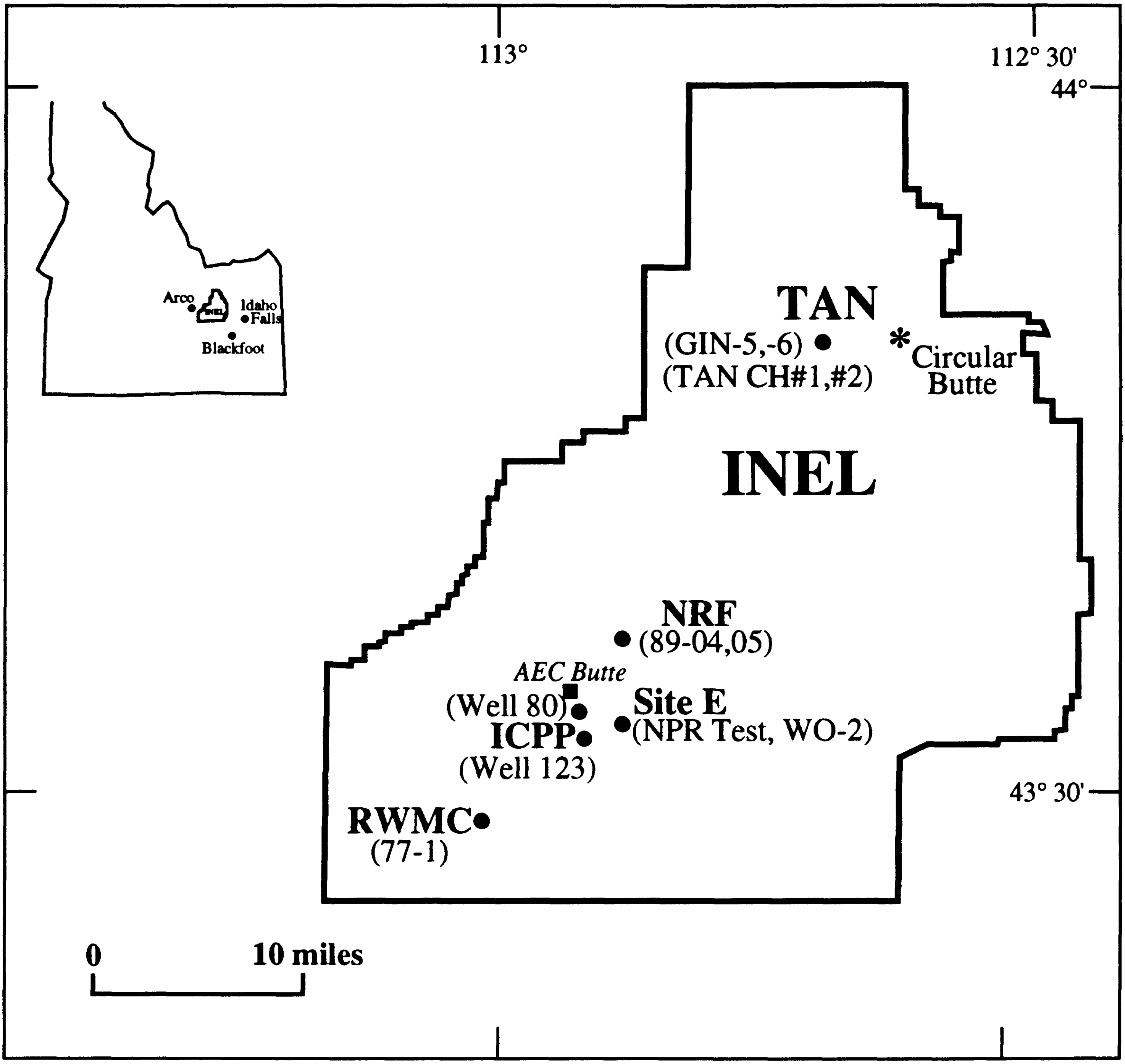

Figure 1. Location map showing the boundary of the Idaho National Engineering Laboratory, certain facilities areas, and the coreholes studied in this investigation.

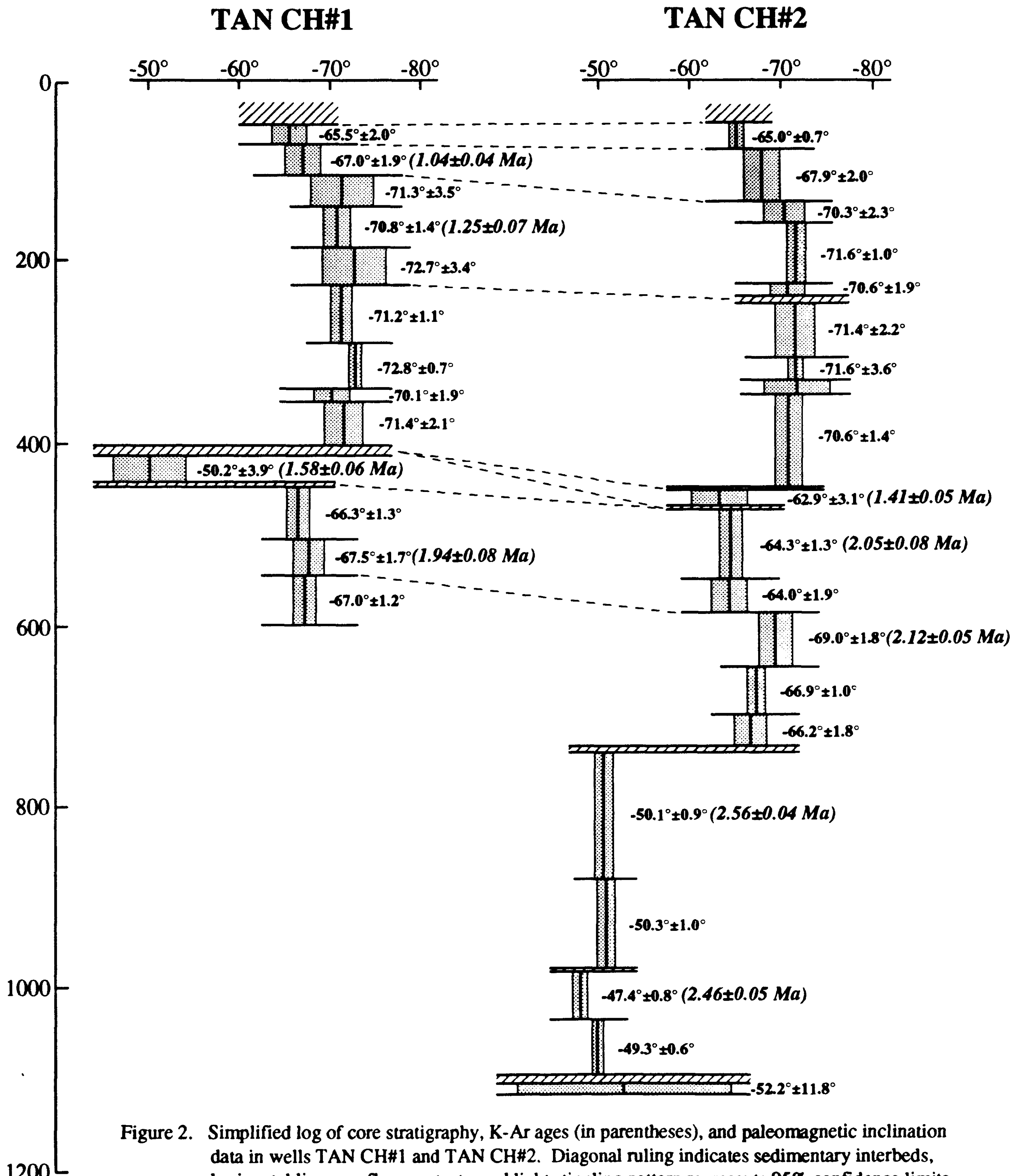

Figure 2. Simplified log of core stratigraphy, K-Ar ages (in parentheses), and paleomagnetic inclination data in wells TAN CH#1 and TAN CH#2. Diagonal ruling indicates sedimentary interbeds, horizontal lines are flow contacts, and light stippling pattern represents 95% confidence limits around the mean inclination values. Dashed lines represent correlations based on paleomagnetic and petrographic data described in this report.

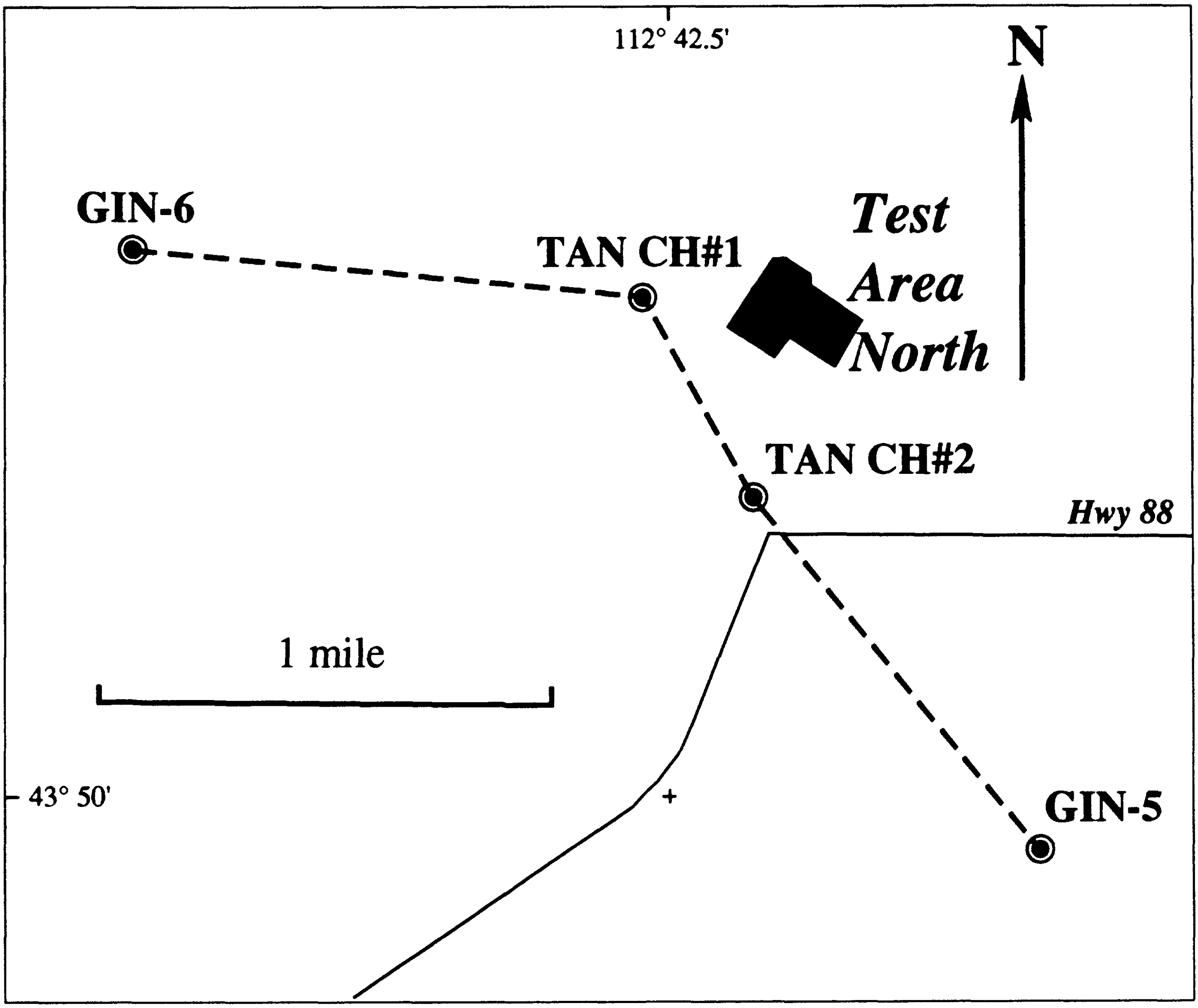

Figure 3. Location map showing the position of the four coreholes studied in this investigation of the Test Area North (TAN) area.

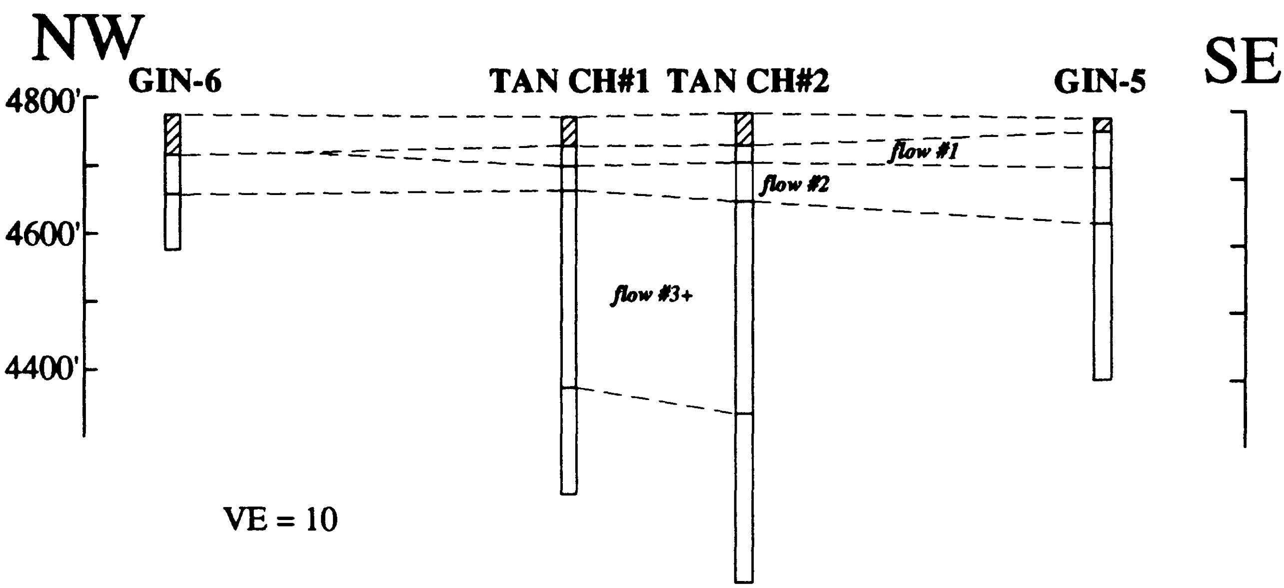

Figure 4. Vertical line of cross-section through the four coreholes studied in the TAN area. Diagonal ruling indicates surface sediments. Dashed lines connect contacts between different numbered flows in the coreholes. Flow 1 pinches out to the west between Tan CH#1 and GIN-6; flow 2 thins at the location of TAN CH#1. Vertical exaggeration equals 10.

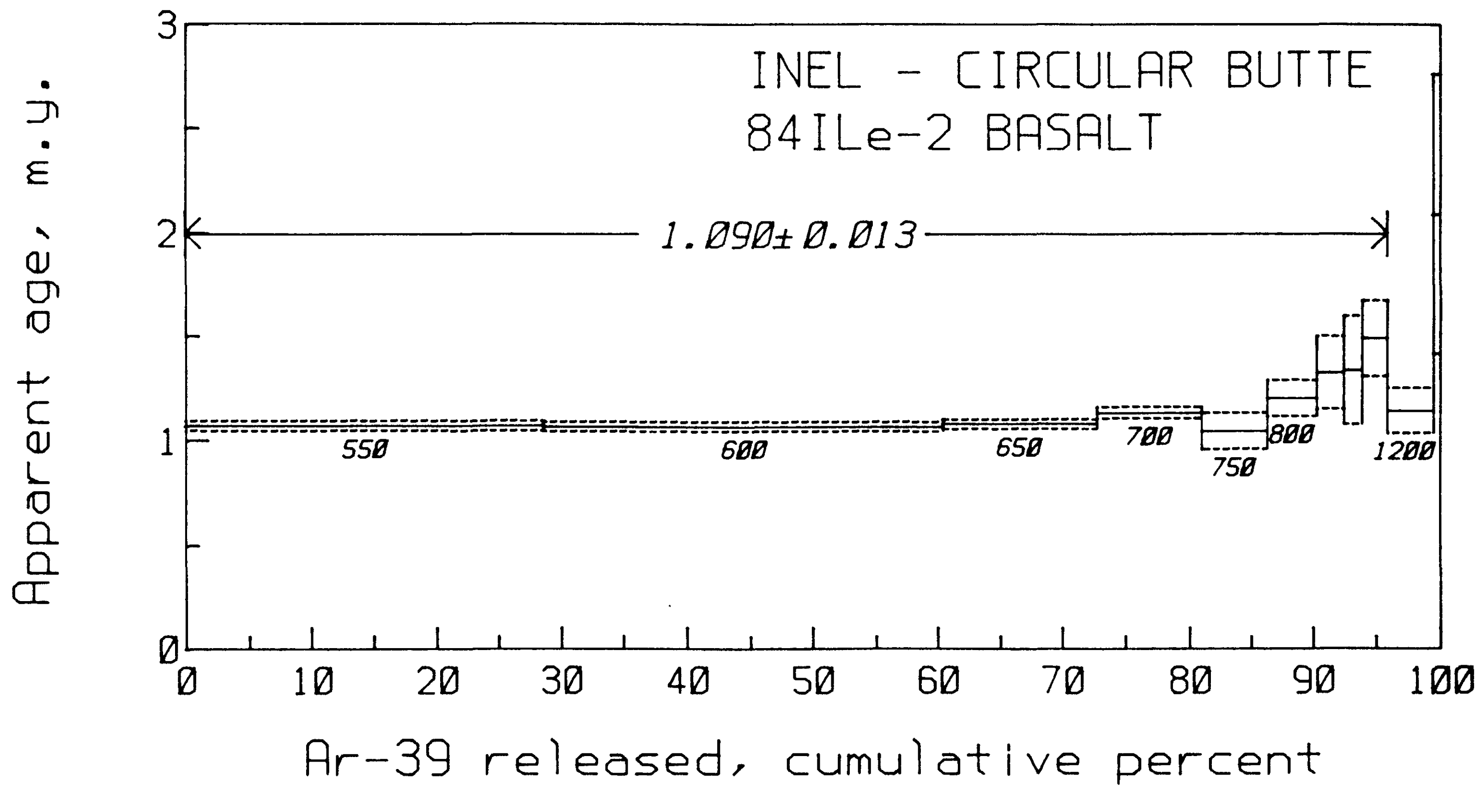

Figure 5. $^{40}Ar/^{39}Ar$ age spectrum diagram for lava of Circular Butte

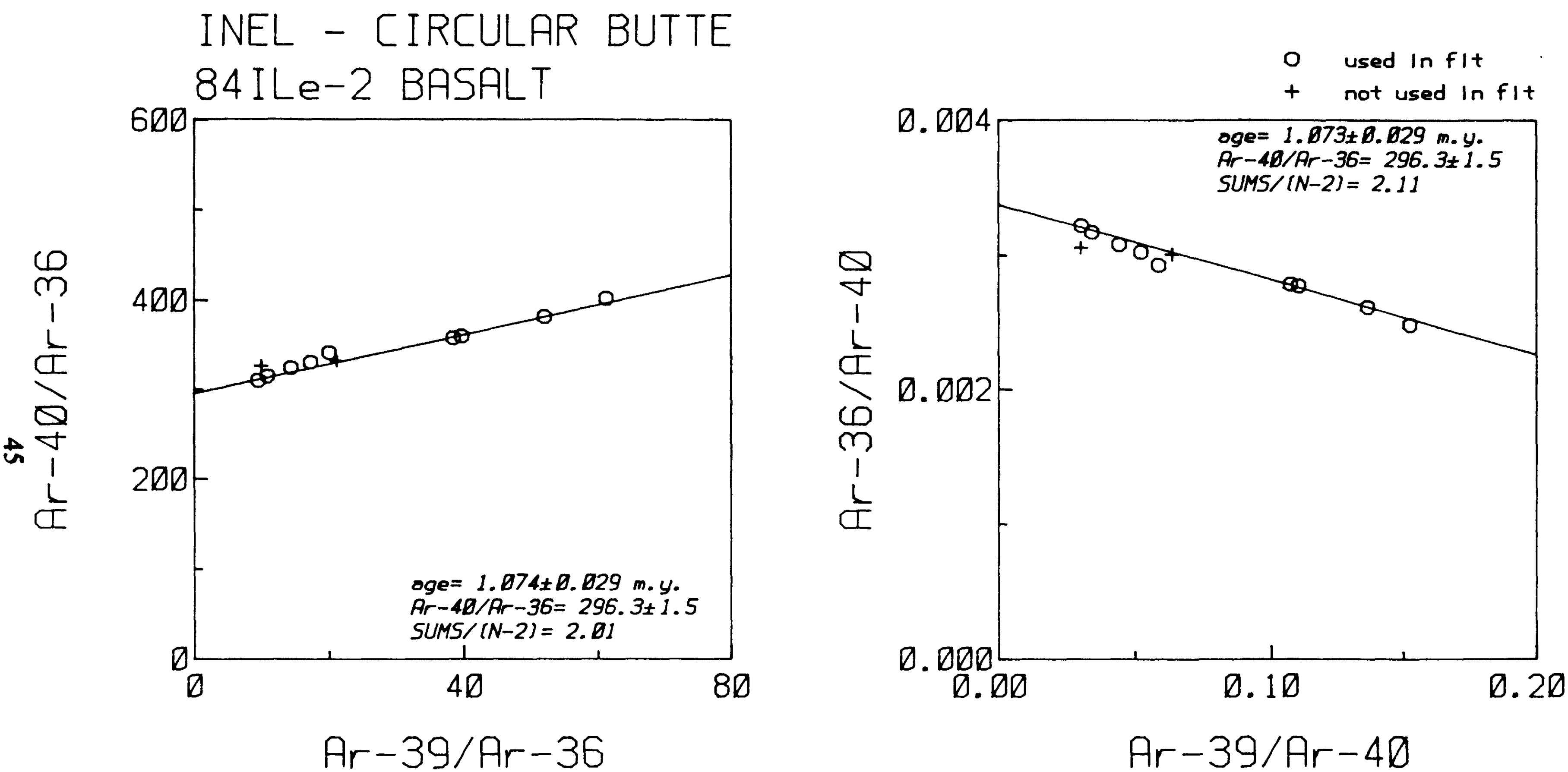

Figure 6. $^{40}Ar/^{39}Ar$ isotope correlation diagrams for lava of Circular Butte

Table 1: Potassium-argon ages and analytical data for basalt samples from TAN CH#1, Idaho National Engineering Laboratory

Flow	Sample	Depth (ft)	K_2O* wt %	$^{40}Ar_{rad}$ (10^{-12} mol/g)	$^{40}Ar_{rad}$ %	Calculated ages, Ma[@] sample age	flow age[#]
2	1-87	87	0.728 ± 0.003	1.063	6.4	1.014 ± 0.062	
				1.055	6.4	1.007 ± 0.061	1.044 ± 0.035
				1.162	7.0	1.109 ± 0.061	
4	1-175	175	0.702 ± 0.002	1.282	4.9	1.269 ± 0.101	1.248 ± 0.069
				1.243	5.1	1.229 ± 0.094	
10B	1-438	438	0.440 ± 0.002	0.9816	7.7	1.550 ± 0.080	1.581 ± 0.057
				1.021	7.7	1.612 ± 0.081	
13	1-523	523	0.438 ± 0.004	1.282	6.9	2.032 ± 0.116	1.936 ± 0.083
				1.156	6.0	1.833 ± 0.120	

* Mean and standard deviation of four measurements.

@ λ_ε=0.581 x 10^{-10}yr^{-1}; λ_β=4.962 x 10^{-10}yr^{-1}; ^{40}K/K=1.167 x 10^{-4} mol/mol. Errors are estimates of the standard deviation of analytical precision.

\# Weighted mean of samples ages, where weighting is by the inverse of the variance, and weighted standard deviation.

Table 2: Potassium-argon ages and analytical data for basalt samples from TAN CH#2, Idaho National Engineering Laboratory

Flow	Sample	Depth (ft)	K_2O* wt %	$^{40}Ar_{rad}$ (10^{-12} mol/g)	$^{40}Ar_{rad}$ %	Calculated ages, Ma[a] sample age	flow age[#]
10A	2-467	467	0.401 ± 0.001	0.7992	8.3	1.384 ± 0.065	1.412 ± 0.047
				0.8335	8.4	1.443 ± 0.068	
11	2-534	534	0.633 ± 0.002	1.696	5.7	1.861 ± 0.127	2.053 ± 0.079
				1.987	6.0	2.180 ± 0.141	
				1.981	5.8	2.174 ± 0.147	
14	2-637	637	0.406 ± 0.010	1.254	26.2	2.142 ± 0.068	2.115 ± 0.046
				1.224	26.7	2.091 ± 0.063	
17	2-785	785	0.503 ± 0.004	1.791	27.8	2.470 ± 0.045	2.556 ± 0.035
				1.943	27.4	2.680 ± 0.054	
19	2-1006	1006	0.613± 0.008	2.162	13.8	2.448 ± 0.068	2.459 ± 0.046
				2.181	15.3	2.469 ± 0.062	

* Mean and standard deviation of four measurements

[a] $\lambda_{\varepsilon} = 0.581 \times 10^{-10} yr^{-1}$; $\lambda_{\beta} = 4.962 \times 10^{-10} yr^{-1}$. $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol. Errors are estimates of the standard deviation of analytical precision

[#] Weighted mean of sample ages, where weighting is by the inverse of the variance, and weighted standard deviation.

Table 3: Potassium-argon ages and analytical data for 84ILe-2 basalt,
Idaho National Engineering Laboratory

Location	K_2O* wt %	$^{40}Ar_{rad}$ (10^{-12} mol/g)	$^{40}Ar_{rad}$ %	Calculated ages, Ma[@] sample age	flow age[#]
Circular Butte: Circular Butte quadrangle, SE1/4, SE1/4 section 13, T. 6N, R. 32E	0.678 ± 0.003	1.187	9.6	1.216 ± 0.050	1.094 ± 0.086
		1.018	6.9	1.043 ± 0.062	
		0.8992	5.1	0.921 ± 0.070	

* Mean and standard deviation of four measurements.

@ λ_{ε}=0.581 x $10^{-10}yr^{-1}$; λ_{β}=4.962 x $10^{-10}yr^{-1}$; $^{40}K/K$=1.167 x 10^{-4} mol/mol. Errors are estimates of the standard deviation of analytical precision.

\# Weighted mean of samples ages, where weighting is by the inverse of the variance, and weighted standard deviation.

Table 4 : $^{40}Ar/^{39}Ar$ analytical data for 84lLc-2 basalt, Idaho National Engineering Laboratory, Idaho
[J=0.0036214]

Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar_{rad}$ (10^{-15}mol)	$^{40}Ar_{rad}$ (%)	$^{39}Ar_{Ca}$ (%)	$^{36}Ar_{Ca}$ (%)	K/Ca	Age (Ma)
550	9.285	5.207	0.0273	25.03	17.6	0.3	5.1	0.094	1.073 ± 0.024
600	9.042	4.219	0.0262	27.68	18.0	0.3	4.3	0.116	1.067 ± 0.023
650	7.313	2.776	0.0199	10.80	22.6	0.2	3.8	0.176	1.081 ± 0.023
700	6.541	2.529	0.0169	7.64	26.5	0.2	4.0	0.193	1.135 ± 0.028
750	32.19	27.63	0.111	4.57	4.9	1.9	6.7	0.017	1.047 ± 0.089
800	28.33	42.83	0.101	3.94	6.3	2.9	11.4	0.011	1.205 ± 0.087
850	21.98	39.17	0.0782	2.35	9.0	2.6	13.5	0.012	1.327 ± 0.175
900	18.63	36.41	0.0660	1.53	10.7	2.4	14.8	0.013	1.339 ± 0.260
1000	16.58	33.88	0.0577	2.46	13.5	2.3	15.8	0.014	1.494 ± 0.183
1200	15.32	33.15	0.0549	3.29	11.2	2.2	16.2	0.014	1.145 ± 0.109
1400	32.28	30.07	0.107	0.92	9.7	2.0	7.6	0.016	2.089 ± 0.672

Ratios corrected for ^{37}Ar decay (half-life=35.1 days) and ^{39}Ar decay (half-life=269 years). Subscripts: rad, radiogenic; K, potassium-derived; Ca, calcium-derived. Decay constants: $\lambda_\epsilon=0.581 \times 10^{-10} yr^{-1}$, $\lambda_\beta=4.692 \times 10^{-10} yr^{-1}$. Errors assigned are estimates of the standard deviation of analytical precision and do not include the error in J, which is 0.5%.